Examining the relationship between leadership and megascience projects

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I hereby declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Signature…………………………….

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Doctor of Philosophy in Technology and Innovation Management

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Summary

A development over the past 70 to 80 years within scientific research has been the need for very large pieces of apparatus to enable the exploration of new scientific topics, particularly within particle physics and space science. These ‘megascience projects’ are generally undertaken as cooperative ventures by countries seeking to pursue scientific experimental opportunities in these fields. Such projects, a subcategory of large/megaprojects that have a minimum budget of one billion US dollars, are characterised by high levels of technological uncertainty, given that their success depends on the development of new, highly-advanced technologies . However, there is a notable lack of research into the *leadership* of megascience projects - an important consideration when embarking on a substantial project. The leadership literature traditionally categorises leaders into five discrete leadership styles, but there is a gap when it comes to understanding the characteristics and development of leaders of megascience projects. In this thesis, I address this gap in knowledge, focusing on three research questions: (1) What are the characteristics of those who lead megascience projects? (2) Where were their leadership skills developed? (3) And how were their leadership skills developed? A useful concept during the intellectual journey to answer these questions was ‘the heterogeneous engineer’, which provided the original conceptual framework for this thesis.

I use a combination of archival and interview-based research to answer these research questions in the cases of the Tevatron at Fermilab in the United States, and the Large Hadron Collider (LHC) at CERN on the Franco-Swiss border near Geneva. This archival research notably required access to normally restricted sections of the CERN archives related to the LHC. The thematic analysis conducted for this research yielded various findings that include the primacy of technical competence as a foundation for respect, along with strong management ability, the importance of trustworthiness, and team empowerment. Furthermore, I found that leadership training within megascience projects is experiential in nature, with formal leadership training programmes acting at most in a support role. During the analysis of my data, I concluded that the heterogeneous engineer concept was based on a relative anomaly, making it difficult to use this concept as the foundation for a more generalised leadership theory. One unexpected finding, which represents a relatively original contribution of this thesis, is the tailoring of senior leadership selection to suit a specific project phase, something which appears to partially contradict the current literature. I identify four phases, the characteristics of leaders best equipped for each phase, and the implications for other large projects.

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Chapter 1 - Introduction

This thesis aims to investigate the relationship between leadership and megascience projects. The main justification for this thesis is based on the reasoning that there is insufficient research into leadership in megascience projects and into the relationship between leadership and successful project management. In relation to the first reason, there seems to be no substantial body of research into leaders of megascience projects. Although there is some work investigating experimental collaborations, such work has generally tried to develop theory from one collaboration (Liyanage and Boisot, 2011). Hence, research looking at far larger accelerator projects may be beneficial, as Shenhar (1993) stated that the technological uncertainty of a project can affect the appropriate management practice that a project leader should take towards the implementation of the project such as design changes, schedule delays, or budget overruns, with tolerance of such issues increasing with the technological uncertainty. It follows that research should seek to identify the characteristics of successful project leaders[1] to benefit future megascience projects. Chaiy *et al.* (2009) noted the success of established methodologies in other non-scientific fields and proposed to capture best practices in large scientific projects to create a single body of knowledge which documents current practices. It should be noted that Chaiy *et al.* (2009) considered only international science projects with a total budget of at least one billion US dollars, which established the budgetary scale for megascience projects. I elaborate on the definition used for megascience projects in Section 2.4.1. Shenhar and Dvir (1996) argued that other large projects associated with civil infrastructure are generally associated with a relatively low level of technological uncertainty, whereas megascience projects can often involve a very high level of technological uncertainty. It is likely that the principle of using standardised methodologies and timetables for projects with a low level of technological uncertainty may not transfer to highly technologically uncertain projects (Shenhar and Dvir, 1996). I therefore suggest that megascience projects may be best treated as a subcategory of large projects with certain specific characteristics such as this high level of technological uncertainty. This thesis will aim to fill this gap to reveal the characteristics of leaders in

[1] It is noted here that that there is a difference between management and leadership; this will be examined in detail in the literature review chapter.

megascience projects and explore the implications for other large projects. I examine the issue of technological uncertainty in Section 2.4.3.

A second reason for this thesis is the important role that leadership plays in relation to successful project management (Pinto and Slevin, 1988; Gemuenden and Lechler, 1997; Lechler, 2000; Pinto, 2012). While there are many factors that can affect the success of a project, effective leadership is often considered to be important (Gemuenden and Lechler; Lechler, 2000). Good leaders can inspire confidence in others and turn challenging situations to their advantage (Pinto and Slevin, 1988; Pinto, 2012). Current project management literature has focussed on management procedures rather than on leadership and its role in within large projects. Zaccaro (2007) provided limited evidence linking trait differences in individuals to effective leadership. This poses several questions regarding whether these characteristics are malleable or rigid (Hoffman *et al.*, 2011). This has not been studied in the case of megascience leaders or in large project leaders. Thus, there exists a gap in current knowledge linking leadership styles to the success of megascience projects. This thesis aims to fill this gap in knowledge. This is considered in detail in Chapter 2.

In this thesis I investigate two case studies of megascience projects to produce findings that may have implications for other large projects – the Tevatron at Fermilab and the Large Hadron Collider (LHC) at CERN. The theoretical foundations for this thesis lie in both the leadership and project management literature, thereby linking two bodies of work to study this important, under-researched topic. Hitherto, research has focused mainly on the management of large projects in non-scientific fields or on leadership in a more generalised context (Vickerman, 1994). I use archival and interview methods to identify the characteristics of those who lead megascience projects. The thesis also explains where and how these leaders developed. The subject of this thesis is important because these megascience projects require investments of at least one billion US dollars, and there is currently a lack of understanding regarding the characteristics of leaders of such projects. With such large sums invested into the project, stakeholders will desire outcomes that deliver the project on time and on cost, and leadership is one factor that can affect the outcome (Gemuenden and Lechler; Lechler, 2000). This thesis aims to provide an understanding of leadership within these megascience projects to put laboratories and other consortia embarking on large projects in a stronger position to identify and train future leaders who can command the confidence of their peers and stakeholders.

The research questions that this thesis aims to answer are:

1. What are the characteristics of those who lead megascience projects?
2. Where were their leadership skills developed?
3. How were their leadership skills developed?

1.1 - Overview and characteristics of megascience

In this section, I briefly outline how the scientific community transitioned from a situation where science was a product of individual work to where many experiments involve the coordinated efforts of hundreds or even thousands of individuals. As recently as the early part of the twentieth century, the level of investment and technical skill required to conduct an experiment was sufficiently low that it was possible for an individual to make significant discoveries. For example, the majority of major discoveries made in electromagnetism during the nineteenth century are attributed to individuals or duos (Grant and Phillips, 2013). While there existed many laboratories with large workforces during this period, each researcher was working on their own experiments in isolation; the Cavendish Laboratory in Cambridge, UK is one example of this (Devons, 1974; Thomson, 1974). The Radiation Laboratory[2] at the University of California, Berkeley, USA is generally considered to be the location of the first large-scale science project in which the entire laboratory is dedicated toward a single experimental programme (Seidel, 1992). Under the directorship of Ernest Lawrence in the 1930s, the laboratory was organised to resemble a large corporation (Heilbron and Seidel, 1989; Seidel, 1992). This important change is one that marked the transition of science from the work of a single individual to a larger collaborative enterprise that also led to the development of megascience projects. Many scientists who subsequently wielded significant influence over post-war American science trained at the Radiation Laboratory, with this group becoming known as ‘Lawrence’s boys’ (Heilbron *et al.*, 1981b; Seidel, 1992; Hoddeson *et al.*, 2008).

During this period, laboratories and experiments were funded primarily through philanthropic contributions or corporate investments (Seidel, 1992). However, the Second

[2] This laboratory has since been renamed the Lawrence Berkeley Laboratory (LBL) in tribute to its founding director. The name Radiation Laboratory was also associated an MIT affiliated laboratory in the 1940s. Their respective workforces often referred to each as the ‘Rad Lab’.

World War forced governments to take a significant role in the funding of science to develop new munitions such as the atomic bomb (Hughes, 2002). The scientific leader for the development of the atomic bomb was Robert Oppenheimer, and he was tasked with the unusual challenge of running a military project with a highly segregated military hierarchy but using civilian workers (Hoddeson, 1992; Hughes, 2002). This project became known as the 'Manhattan Project' (Hoddeson, 1992). Unanticipated technical challenges drove Oppenheimer to introduce a new, problem-focused approach (Hoddeson, 1992; Hughes, 2002; Grey and Sturdy, 2009; Grey and Sturdy, 2010; Lenfle and Loch 2010). One specific challenge arose during the development of the plutonium component of the Manhattan project because impurities in industrially produced plutonium would have led to a bomb that would have 'fizzled' rather than exploded (Hoddeson, 1992). There was an alternative explosive method, and in order to re-align the effort toward this new method, the segregated divisions were replaced with temporary interdisciplinary teams formed in response to issues as they emerged (Hoddeson, 1992). It could be argued that Oppenheimer's relative autonomy gave him sufficient flexibility to make sweeping organisational changes, indicating that the leadership response to scientific challenges can be an important factor in achieving success (Hoddeson, 1992; Gibbons *et al.*, 1994).

Towards the end of the Second World War, there was a debate in the United States about the future relationship between science and government. Senator Kilgore's vision of a National Science Foundation was designed to diversify research and prevent 'patent pooling', the hoarding of patents by a small number of large corporations (Berge, 1945; Kevles, 1977). In response to this initiative, those who were opposed to what they considered government 'meddling' in science commissioned a report entitled 'The Endless Frontier' (Kevles, 1977). The author of this report, Vannevar Bush, portrayed science as a new frontier offering unlimited benefits (United States Office of Scientific Research and Development and Bush, 1945; Kevles, 1977). The resulting compromise established a National Science Foundation with a less interventionist role than desired by Kilgore (Kevles, 1977). This budget of the National Science Foundation was rather modest until 1957, when the launch of Sputnik resulted in massive budget increases (Kevles, 1977; Galison and Hevly, 1992). These budget increases created the appearance of an unlimited funding environment, which allowed the production of scientific knowledge on an industrial scale, termed most famously by De Solla Price (1963) as 'Big Science'.

Hughes (1998) also charted the growth of major American technology projects wherein engineers generally took the dominant role rather than scientists. Many authors (such as those above) have portrayed these very large technological projects as having first begun at UC Berkeley with many working on the Manhattan Project before dispersing to their own civilian laboratories (Galison and Hevly, 1992; Hoddeson *et al.*, 2008). However, Hughes (1998) describes large technological projects as something that also occurred in engineering before the Second World War where a number of 'heroic inventors' in the Eastern United States operated in companies such as the Ford Motor Company.

Many engineers moved into military work as the Cold War arms race began, a point that Hughes (1998) identifies as the genesis of the large technical system. These military projects attempted to construct highly complex systems to track flying objects and deliver payloads between continents (Hughes, 1998; Hughes, 2004). This included the SAGE project and the Atlas missile respectively (Hughes, 1998; Lenfle and Loch, 2010; Morris, 2013). Many of the tools developed in the context of these projects then diffused into other American government and civilian projects before coming to Europe through NATO joint ventures (Morris, 2013). Hughes (1998) characterises many of the leaders in these large technical system projects as 'systems builders'. I will consider the management of the SAGE and ATLAS projects and the concept of the 'systems builder' in Section 2.5.2.

Despite a popular reference to the growth in science generally and particularly in laboratory size as 'Big Science' (De Solla Price, 1963; Weinberg, 1969), there are others who have made a distinction between 'Big Science' and 'Megascience' (Hoddeson *et al.*, 2008). De Solla Price (1963) and Weinberg (1969) described the post-war expansion of scientific research as 'Big Science': yet at that time, large scientific projects were sufficiently rare that categorisation was not a pressing concern for scholars. Hoddeson *et al.* (2008) argued that megascience evolved during the 1970s Oil Crisis, which was characterised by rather aggressive financial constraints in most areas of government budgets. Larger projects, notably those at the particle physics laboratory Fermilab in the 1970s, opened up new avenues of scientific enquiry and could secure long-term government funding (Krige, 1997; Hoddeson *et al.*, 2008). The increase in size and scope of these particle physics projects and experiments soon led to a situation where it became difficult to identify a clear project endpoint (Krige, 1997; Hoddeson *et al.*, 2008). Each experiment led to further upgrades to answer additional questions, so judging when the project ends could be somewhat problematic. A fuller definition of megascience is provided in Section 2.4.1.

1.2 - Overview of bodies of relevant literature

1.2.1 - Leadership

Although there is some literature investigating leadership within project structures including projects in the physical and biological sciences considered in Section 2.1, the leadership literature can be broadly divided into two paradigms. One paradigm categorises leaders into five discrete styles based on their behaviours – namely transformational, transactional, laissez-faire, authoritarian, and democratic leadership styles (Bass, 1990). Leaders exhibiting certain characteristics that are unique to each style can be categorised. Several of the styles have interrelated components and some have a symbiotic relationship with one another (Bass, 1990). This is explored in detail in Section 2.2.

The other paradigm, which dominated the leadership literature for over a century but has since fallen into disfavour (Galton, 1869; Virkus, 2009), is found in the proposition that leaders are 'born great' and the analysis of their evolution can be used as a foundation for theory development. There are four primary models for assessing this evolution. These are trait theory, skills theory, situational theory, and contingency theory. I discuss these models in Section 2.3.

1.2.2 - Project management

The projects under investigation, namely the Tevatron and the LHC, are megascience projects with budgets in the billions of US dollars and a total labour force numbering in the thousands. The high technology nature of the projects has also resulted in novel technological developments, for instance, the use of liquid helium-cooled superconducting magnets and the '2 in 1' magnet system (Tollestrup, 1996; Evans, 2009). Using liquid helium to cool the superconducting magnets in the Tevatron allowed the creation of a stronger magnetic field at lower running costs which enabled scientists to investigate higher energy collisions despite reductions in operating costs at Fermilab (Tollestrup, 1996). The '2 in 1' magnet system for the LHC was also novel in that two beam pipes used the same magnetic and cryogenic systems, substantially reducing space usage and running costs in the cramped LHC tunnel (Evans, 2009). The levels of technological uncertainty in these megascience projects are considerably higher than in most large projects, so I chose to investigate megascience projects as a subcategory of large projects and to consider the technologically uncertain project literature during my literature review.

In the case of technologically uncertain projects, the literature indicates that projects with greater levels of technological uncertainty require greater flexibility toward cost and schedule overruns. Shenhar and Dvir (1996) proposed a classification system for assessing this technological uncertainty. On this basis, a more technologically uncertain project requires greater tolerance of budget and/or schedule overruns, which could be incompatible with some of the practices associated with large projects (See below). Megascience projects generally match the characteristics of the class C ‘High’ uncertainty – considered to be the first practical use of existing technologies, or class D associated with ‘Super High’ uncertainty - projects where technologies must be developed in the context of application (Shenhar, 1993; Shenhar and Dvir, 1996)[3]. Great care must be taken to appropriately classify a project, since imprecise assessment may result in fundamentally flawed management assumptions (Shenhar, 1993; Shenhar and Dvir, 1996). It is equally important to match a suitable leadership style to the project type, with ‘transformational leadership’, for instance, becoming more appropriate with increasing technological uncertainty (Shenhar and Dvir, 1996). The Shenhar and Dvir (1996) classification system and the concept of a ‘matching process’ is examined in detail in Sections 2.4.2 and 2.4.3 respectively. These megascience projects require a project leader to have the management abilities to handle unexpected issues, which may necessitate delays and increased costs, yet the size of the project means that stakeholders do not want costs to rise uncontrollably.

Large projects, which have budgets in the billion US dollar range also exhibit certain characteristics that differentiate them from other types of project. Mersino (2007) identified these as notably including the use of subcontractors, virtual team working, and

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[3] In the rest of the thesis I primarily refer to ‘High’ and ‘Super High’ classification projects by the terms ‘C’ class and ‘D’ class projects respectively.

the project's level of importance to the main organisation and therefore a greater degree of oversight. However, these large projects usually incorporate well-understood technologies such as railways, bridges, and tunnels. By contrast, megascience projects incorporate technologies that are occasionally developed in the context of application. Therefore they appear to have novel characteristics of technological uncertainty that most large projects do not have. This offers the possibility that leaders in megascience projects might display styles involving a combination of leadership characteristics observed in technically uncertain and large projects, making this topic a worthy subject for investigation. It was therefore beneficial to analyse the relevant project management literature associated with technologically uncertain and large projects. Section 2.4 explores the project management literature in detail.

1.3 - Conceptual framework

During the literature search conducted during the early stages of my research, it became apparent that, despite the scientific community working together for the benefit of the discipline, certain individuals received additional credit for the work. This credit often involved receiving the title of 'father' of an experiment or having academic 'sons' (Heilbron and Seidel, 1989; Krige, 2001). One particularly important paper by Krige (2001) on the role of Carlo Rubbia in the Nobel Prize-winning discovery of the W and Z bosons, theorised that some individuals could mobilise both the human and the material resources necessary to attain such ambitious objectives. Such individuals were described as 'heterogeneous engineers'. The conceptual framework originally chosen for this thesis utilised this concept of the heterogeneous engineer, a concept briefly mentioned by Hughes (1987) and Law (1987b) but expanded on by Krige (2001). This term is influenced by the Law's (1987a) theory of heterogeneous engineering, a social explanation of technical change – this theory describes how technical systems are composed of various social and technical elements. Law (1987a) illustrated his theories using the Portuguese naval fleet in the 1600s, which incorporated new developments into their ships (Law, 1987a). I examine this concept in detail in Section 2.7, which sets out the conceptual framework.

In terms of practice, there is little knowledge of the characteristics of those who lead megascience projects or the training they underwent to be adequately prepared for leadership. This thesis also provides a basis for deriving insights regarding how the scientific community identifies future scientific leaders and develops them with some implications for other non-scientific large projects.

To summarise, the gaps identified in the literature review in Chapter 2 give rise to the research questions. To reiterate, these questions are:

1. What are the characteristics of those who lead successful megascience projects?

2. Where were their leadership skills developed?

3. How were their leadership skills developed?

1.4 - Outline of this thesis

The remaining chapters of this thesis are organised as follows:

Chapter 2 – Literature Review

This chapter provides a detailed overview of the two bodies of literature that inform this research and further strengthens the justification for the choice of topic and research questions. These two bodies of literature are those on leadership and project management. This thesis aims to cast light on the types of leaders within megascience projects. Its findings may also be relevant to similarly large projects, providing future opportunities for a comparison between leaders in other large projects and megascience projects.

Chapter 3 – Methodology

This chapter provides an examination and justification of the methods that I adopted for this research, namely archival and interview research as a basis for building case studies. I conducted the archival research on-site at Fermilab in Chicago, USA and CERN in Geneva, Switzerland. The archival research provided an insight into internal project management procedures and the identification of whether there is, or has been, any consideration of leadership throughout these projects. The archival material also allowed triangulation of evidence during the interview research phase, providing a stronger foundation for any subsequent findings. I completed the interview research primarily at Fermilab and CERN except in certain cases where it was necessary to travel to other locations to meet with key individuals.

A combination of archival research and interviews offered the opportunity for direct contact with these leaders to obtain first-hand information on leadership characteristics and the possibility to triangulate claims made in one research phase with the other. This is examined in detail in Sections 3.3 and 3.4.

Chapters 4 and 5 – Case studies

These present the case studies as two separate chapters, one on the Tevatron and the other on the LHC, built up using the methods described in Chapter 3. All relevant factors are considered as the data is introduced. Each case study provides a general introduction and brief description of the accelerator and organisation responsible. In some cases, this short introductory information may provide an internal context, explaining how and why certain leadership styles may be more effective than others may and why these ideal styles may differ between projects. More detailed contextual information on the project and laboratory is contained in Appendix 1.

The main part of each case study is devoted to data derived from fieldwork. Each case study considers the attitudes of the scientists whom I interviewed towards the five leadership styles considered in Section 2.2 as these styles acted as discussion prompts. I also discuss the characteristics and development of leaders at each respective laboratory. The final section examined additional findings that emerged from the case studies which are not directly related to the original research questions.

Chapter 4 – Case Study 1 - The Tevatron at Fermilab

The Tevatron at Fermilab in the United States was a particle accelerator whose construction began in the late 1970s and concluded in 1983: final closure was in 2011 (Hoddeson *et al.*, 2008; Oddone, 2011). It was the most powerful accelerator in the world when operating in collider mode until it was overtaken by the LHC in 2010 (Perkins, 2000; Hoddeson *et al.*, 2008; Riordan *et al.*, 2015). The Tevatron enabled the discovery of new particles such as the top quark and helped bring about a better understanding of already discovered particles over its runtime before its closure due to budget cuts (Krige, 2001; Hoddeson *et al.*, 2008; Oddone, 2011). This project met the selection criteria that I outline in Section 3.2. Many consider Fermilab the first truly national laboratory in the United States, open to all researchers rather than discriminating based on institutional affiliation (Lederman, 1963; Wilson, 1970; Hoddeson *et al.*, 2008).

Chapter 5 – Case Study 2 - The Large Hadron Collider (LHC) at CERN

The Large Hadron Collider (LHC) at CERN in the French-Swiss border is a particle accelerator which commenced operation in 2008 (Smith, 2007), and it is still in operation today, with further upgrades planned (Rossi, 2016). It is the most powerful particle accelerator in the world and recently discovered a particle with characteristics that so far match the theoretical predictions of the Higgs boson[4] (Perkins, 2000; Aad *et al.*, 2012). This project also met the criteria for a megascience project that I outline in Section 3.2 and has interesting organisational factors such as its international workforce and position at the current forefront of particle physics research (Smith, 2007). However, while the literature often refers to the LHC as an international project, this claim is usually based on funding mechanisms (Fraser, 1997). Member state[5] contributions primarily fund the LHC while the US government principally funded the Tevatron – which makes the Tevatron appear to be more a ‘domestic’ megascience project (Smith, 2007; Hoddeson *et al.*, 2008; Evans, 2009). Despite this difference in the origin of funding, one cannot ignore the fact that scientists who worked on the Tevatron came from all over the world. The investigation of a collider still in operation such as the LHC offered the opportunity to interview experimental collaborators to determine whether the characteristics of leaders in experimental collaborations are different from those for accelerator construction leaders.

Chapter 6 – Discussion

This chapter draws together the findings of each case study to determine what similarities and differences exist in the characteristics and development of leaders between the two case studies. This discussion follows the Yin (1994) principle to understand what is common and what is unique to each case study. The purpose for adopting this Yin (1994) principle is to aggregate the findings from the two case studies and consider alternative explanations to clearly demonstrate the robustness of my findings. These findings are discussed in the light of the literature on leadership and project management. What emerges in this chapter is the primacy of technical competence in both case studies as a

[4] The Higgs boson is the theorised quantum of the Higgs field; a scalar field that determines which particles possess mass and governs the range of the weak nuclear force.

[5] It is noted that in the case of the LHC, there were contributions for the first time from non-CERN member states, although budgets have been historically based exclusively on member state contributions (Smith, 2007).

foundation for respect for leaders, but this must be coupled with other characteristics including management ability and trustworthiness. However, certain differences existed such as in leadership development with future Fermilab leaders developed with an informal ‘apprenticeship’ style of training while CERN incorporated formal classroom training into its leadership development procedures.

During the analysis, I conclude that the concept of the heterogeneous engineer provides an inappropriate conceptual framework for developing broader leadership theories. The information from the fieldwork demonstrates that much of the heterogeneous engineer concept was developed based on a relative anomaly, and using it to build broader leadership theories is therefore inappropriate. I found that the five leadership styles, which I consider in Section 2.2, proved more useful as tools for understanding the nature of leadership in megascience projects. I also discuss the finding that forms a substantial contribution of this thesis, namely that different senior laboratory leaders were selected to enable specific project phases. I observed four phases in which each laboratory tailored the selection of different types of senior leaders to meet the specific needs of each phase. These four project phases are initiation, approval, construction, and exploitation. I also map these four project phases onto pre-existing project life cycles to determine the extent of its novelty and whether this finding has any implications for other large projects.

Chapter 7 - Conclusion

This final chapter summarises the main findings and contributions to knowledge. In addition, the conclusion considers the leadership and policy implications that arise from these findings, while also acknowledging its limitations. These limitations may affect the ability to generalise this research but offer interesting future research opportunities. I outline how I might exploit these opportunities.

Appendix 1 - Brief histories of the Tevatron and the LHC

In Chapters 4 and 5, which comprise the case studies of the Tevatron and LHC respectively, I briefly summarise the host laboratories and the projects. Appendix 1 sets out a longer version of these histories. This appendix provides an extended project timeline with additional context and informs decisions taken by leaders during their respective projects.

Appendix 2 – Research documents

The fieldwork necessitated the creation of certain documents to ensure the process ran smoothly and in accordance with relevant professional and legal obligations. This appendix provides copies of these documents used during the fieldwork process. These were interviewee information sheets, consent forms, and the questionnaires used during the fieldwork at Fermilab and CERN.

Chapter 2 – Literature Review

This chapter comprises an analysis of the two primary bodies of literature that will help to inform and to provide further justification for the research questions of this thesis. These bodies of literature relate to leadership and project management. Section 2.1presents an analysis of the relevant leadership literature. Sections 2.2 and 2.3 examine the two primary leadership paradigms, the style model and evolutionary model. Section 2.4 considers the relevant project management literature in the light of the research questions that this thesis seeks to answer.

During the literature search, other bodies of literature became apparent but I considered them less relevant to this thesis. Section 2.5 briefly describes these other bodies of literature concerning complex product systems, sociotechnical systems, and large technical systems and explains why they are not central to this particular study. As a result of my literature review, I identify a gap in existing knowledge and devise research questions in Section 2.6 to address this gap. Section 2.7 compares two potential conceptual frameworks and presents the notion of heterogeneous engineer, which this thesis adopts for its analysis. Finally, Section 2.8 summarises this chapter.

2.1 - Leadership literature

Leadership is considered to be the behaviours embodied in a single individual for the development, motivation, and direction of labour toward the attainment of certain goals (Bass, 1990). Krige *et al.* (1997) described the importance of leadership in megascience projects during the construction of the SPS[6] in the 1970s at CERN. Krige *et al.* (1997) described the selection of a suitable leader as an “urgent question”. However, they did not elaborate on the qualities considered desirable in a project leader. Although there is some work examining leadership within experimental collaborations and project structures, which I consider in Sections 2.1.1 and 2.1.2 respectively, there appears to be no study elucidating the characteristics which a leader should embody in megascience projects (Gluck and Foster, 1975; Wheelwright, 1992; Liyanage and Boisot, 2011; Edmondson, 2012). This is a significant gap in knowledge which this thesis aims to fill. The literature describes a wide variety of leadership styles, but five styles are most commonly used (Bass, 1990). These five leadership styles are transformational,

[6] SPS is the acronym for the Super Proton Synchrotron. It was an accelerator built in the 1970s and it proved extremely versatile, being adapted for later use as an injector for both LEP and the LHC.

transactional, laissez-faire, authoritarian, and democratic (Bass, 1990). The literature often refers to these as the ‘style’ paradigm models (Virkus, 2009). These style paradigm models start from the assumption that leadership is a learned response and replication of certain behaviours creates a desired type of leader. There also exist ‘evolutionary’ paradigm models, based on the principle that leaders are naturally gifted individuals and the analysis of their development acts as a foundation for new theory. There is a variety of methods for analysing this evolution, considered in detail in Section 2.3.

2.1.1 - Leadership within the project structure

In this section I consider the most relevant studies relating to leadership within projects. Megascience projects offer an opportunity for experts from diverse fields to collaborate to design a construct an array of systems incorporating a variety of technologies. Many other projects that incorporate cross-functional teams of experts tend to pursue a fluid team structure whereby individuals within a team join and leave as required, particularly when the outputs of such teams are unique (Mintzberg, 1979; Mintzberg and McHugh, 1985). Edmondson (2012) refers to this as ‘teaming’ although other authors have coined the term ‘adhocracy’ to refer to similar setups (Bennis and Slater, 1968; Toffler, 1970; Mintzberg, 1979). Such types of team are claimed to be effective in the response to unexpected complex challenges as new skillsets can be rapidly brought in as necessary (Edmondson, 2012). Leaders of such teams do not need to be particularly prescriptive to the team but must create an appropriate framework within which the team can organise themselves (Edmondson, 2012). This is similar to the way that CERN has created the framework for experimental collaborations noted in Section 2.1.2. This framework requires ongoing reinforcement from the leader, emphasising the values shared by all team members and the value of well-intentioned disagreements (Edmondson, 2012). However, individuals within the team need to demonstrate self-awareness so they can recognise when to invest their time and skills elsewhere in the project. Otherwise, teams may become excessively large and also lack the skills to solve challenges.

I do not expect there to be a significant amount of ‘teaming’ or ‘adhocracy’ within accelerator construction projects: once the project begins construction, the role of leadership will be to monitor these processes, which involve relatively standardised procedures. However, individuals who served on technical parameter committees at the early stages of the accelerator construction project may describe a teaming process as they seek to answer complex questions such as what type of machine they wish to build, whether it is technically feasible, and if industry can meet the specifications. By contrast, there will likely be significant teaming within the experimental collaborations because of the broader scope of activities that take place. During the early stages of the collaboration, new talent will design the various sub-systems of the detector and determine the most appropriate technologies. Once the detector is assembled, these design or construction-focussed teams will dissolve as the collaboration re-focusses itself around operation and data analysis.

2.1.2 - Leadership within scientific projects

There exists a small body of literature examining leadership in the context of scientists. While some of these are academic studies, other documents are effectively manuals that advise prospective scientific leaders on how to be a leader. This includes suggestions on how a laboratory might differ from other types of organisation, how to manage conflict, and possibilities for recruiting and developing talent (Cohen and Cohen, 2006; Divya and Jonathan, 2006).

An examination of the academic research in this area reveals the fundamental tension within scientific research – research has a creative rebellious element, yet it also requires external coordination and respect for established protocols (Kuhn, 1977; Hackett and Parker, 2012). Therefore, the leader must balance these issues to avoid the respective risks of low productivity and missed opportunities (Hackett and Parker, 2012). Certain documents suggest that scientific leaders have challenges with this balance as they tend to focus on technology and science at the expense of the human element (Gemmill and Wilemon, 1994). This can introduce inefficiencies as a poor group dynamic can be a limiting factor for what is considered 'good' science (Sapienza, 2004). The literature considers good scientific leaders to be able to avoid this trap by paying as much attention to individuals within the group and acting as an example to the other scientists within the team (Hughes, 2004; Sapienza, 2004) by embodying the Mertonian norms (Owen-Smith, 2001). There is an occasional tendency within science for students to emulate their leader. One example of this within science is that of Ernest Lawrence, a prominent scientist at the Radiation Laboratory in the 1930s from Section 1.1, several of whose students sought to emulate both his scientific style and his interest in the arts (Heilbron and Seidel, 1989; Hughes, 2004).

The second main type of literature in this field, namely documents intended to be used as guidebooks for scientific leaders, use the academic literature as a foundation (Sapienza, 2004; Cohen and Cohen, 2006). For example, Cohen and Cohen (2006) devised a questionnaire that allowed a scientist to self-identify their leadership weaknesses before providing specific advice on how to strengthen those areas.

However, there is likely to be a significant difference in the focus for leaders in science and leaders in megascience projects. Leaders in science work on comparatively smaller-scale experiments, designing and constructing their own equipment with the focus being on the scientific experiment to be conducted later. The opportunity to experiment at the end acts as the incentive during the design and construction of the experiment. This broader mission offers the possibility to train future researchers. By contrast, the focus of megascience project leaders will be almost entirely on the design and construction of the equipment. It is rather unlikely that such leaders will operate the machine as it will be handed over to the laboratory departments.

One additional project issue that might affect the characteristics of leaders within science is the scope of the project (Shenhar and Dvir, 1996). Shenhar and Dvir (1996) broadly categorised projects by scope into three categories (See Table 1). These three categories are assembly, system, and array (Shenhar and Dvir, 1996).

Project scope category	**Description**	**Example**
Assembly	Collection of components into a single unit performing limited functions	Household appliance
System	Complex collection of many units and assemblies capable of large scale independent functions	Personal computer
Array	A collection of systems working in conjunction for a common goal	Public transport network

Table 1: The project scope classification system proposed by Shenhar and Dvir (1996)

This terminology is prominent within the large project literature in Section 2.4.4, particularly because many large projects are arrays and there can be issues at the interfaces between systems (Davies *et al.*, 2009; Davies and Mackenzie, 2014). Most scientists working in a laboratory will be working on an assembly project, where several components are assembled into a single unit performing a single task. This also includes experimental collaborators working at their home institution on a single sub-system within a particle physics detector. The experimental spokesperson will likely be the point of contact where these various sub-system assemblies interface to become considered as a system. However, it is not necessary for all detector sub-systems to be working perfectly for the detector system to function.

By contrast, a megascience project leader will have to take charge of the entire accelerator system where all aspects of the machine will have to work perfectly for the accelerator to function. Equally, the senior leader (ie. a leader running an entire laboratory) must manage an array of systems, including liaising with the experimental collaborations, the laboratory infrastructure, and other stakeholders. Although Shenhar and Dvir (1996) formally categorised projects according to their scope, Hughes (1987; 1998; 2004) has also written about projects that are large technical systems, a topic which I consider in Section 2.5.2. The project scope will have likely also affected the characteristics of leaders in megascience projects, an issue which I discuss in Section 6.4.3.

There is one account examining leadership in the case of major experimental collaborations that examines the ATLAS collaboration at CERN (Liyanage and Boisot, 2011). However, it must be noted that this account only examines a single collaboration rather than the two collaborations within this thesis. Nonetheless it is worthwhile considering the findings and it presents the opportunity to determine whether ATLAS is exceptional or whether leaders within experimental collaborations share some common characteristics.

Liyanage and Boisot (2011) identified three different streams of leadership within ATLAS. These three types of leadership are institutional, intellectual, and project.

With regard to the institutional leadership, it is acknowledged that CERN has no formal role in the running of the collaboration (Liyanage and Boisot, 2011). This is an important distinction between an experimental collaboration and the construction of an accelerator, which is traditionally organised within a laboratory context (Hoddeson *et al.*, 2008; Riordan *et al.*, 2015). However, CERN provides an institutional framework that the collaborations can organise within and a stable climate for intellectual and project leadership. In the case of ATLAS, the institutional leadership is provided by CERN.

Intellectual leadership is, by definition, based on the intellectual capability of a leader. If one frequently has excellent ideas and can articulate those ideas to others, whether inside the collaboration or to the rest of the scientific community, they will become intellectual leaders. This stream of leadership feeds into the two types of leadership roles within ATLAS leadership *of* the community and leadership *by* the community. Leadership of the community is granted by peers and leadership by the community is a role within the community. Effectively this distinction is leadership based on respect and a formal position that acts as a manifestation of that respect. A spokesperson of an experimental collaboration cannot achieve that position without first gaining the trust of their peers, an important commodity within ATLAS, most often displayed through the gift of sharing knowledge and credit in scientific papers. There are no ‘heroes’ who take charge from beginning to end, and leaders at ATLAS tend to emerge based on their intellectual capability and humility. This is slightly at odds with some other literature, notably Krige (2001) who identified Carlo Rubbia as playing a ‘heroic role’ for the entirety of a CERN experimental collaboration. I discuss this issue in Section 2.7.3. However, intellectual leaders bring recognition to the collaboration as a whole and can attract new talent to the collaboration (De Solla Price, 1963; Liyanage and Boisot, 2011).

The third and final type of leadership within ATLAS, project leadership, relates to the degree to which a leader can improve the capabilities of their team. Unlike most other types of project, the ATLAS collaboration is made up of research laboratories and universities that have opted to pool their resources. However, while a project manager/leader in most projects controls most of the resources and can direct them as necessary, the ATLAS spokesperson actually controls very little resources directly. Instead the collaborators retain control over the resources from their institutions, forcing a spokesperson to demonstrate a consensus-building style of leadership to bring all parties together and try to create a consensus. By contrast, a leader at problem-focussed levels of the collaboration will have greater powers at their disposal to allocate their own resources to challenges.

The previous two sections considered the relevant studies on leadership within projects and scientific collaborations respectively. In the following sections I examine the more conceptually-orientated leadership literature. Most of the leadership literature can be divided into two paradigms – the style paradigm and the evolutionary paradigm.

2.2 - Style paradigm models

The style paradigm models came to prominence during the early part of the twentieth century following the decline of the evolutionary paradigm models (Barker, 1997). While the evolutionary paradigm models considered in Section 2.3 began from the premise that leadership is an innate trait and therefore analysis should focus on the development of the leader over time, the style paradigm models side-stepped this issue by classifying leaders based on their current behaviour (Barker, 1997). It implies that leaders who adopt specific behaviours can become a certain type of leader and can change further as necessary (Toor and Ofori, 2008; Olaniran *et al.*, 2015). The style paradigm models are composed of five leadership styles that I consider in this section.

2.2.1 - Transformational leadership

The literature characterises transformational leaders seeking to understand and change an existing project or organisational culture (values, norms) to secure superior performance and outcomes (Bass, 1990; Bass and Avolio, 1993; Shamir *et al.*, 1993). According to Kirkpatrick and Locke (1996), transformational leadership has three core components which are communicating a vision, implementing this vision, and demonstrating a charismatic communication style to achieve the vision.

2.2.1.1 - The communication, implementation and achievement of a vision

A transformational leader tends to acquire and retain followers with the communication of a vision (Bass and Avolio, 1993; Mumford *et al.*, 2000). The leader articulates this vision in terms of fundamental human values, which serves to unify and motivate teams (Hater and Bass, 1988; Bass and Avolio, 1993; Shamir *et al.*, 1993; Kirkpatrick and Locke, 1996). This vision makes followers believe their work differentiates them from other workers and creates a collective identity that aligns the interests of the group with the leader (Shamir *et al.*, 1993).

It is also necessary to realise that vision in order to give the leader a base of credibility for delivering projects within the expectations of both followers and the rest of the organisation (Tracey and Hinkin, 1998). The requirement for delivery demonstrates that a transformational leader needs to be able to achieve a vision rather than leave it as an unrealised concept. Kirkpatrick and Locke (1996) claim that towards the end of a project, transformational leaders display characteristics more often associated with transactional leaders (Hater and Bass, 1988). I consider transactional leadership in more detail in Section 2.2.2 below.

An additional component of transformational leadership according to Kirkpatrick and Locke (1996) is charisma. This is exhibited by expressing high performance expectations of followers and confidence in the ability of each team member to achieve that performance level (Shamir *et al.*, 1993). However, the categorisation of charisma as the sole preserve of a single leadership style reduces its utility as a component of leadership, because other leadership styles might exhibit charismatic behaviours, in particular authoritarian leadership, which I consider in Section 2.2.4 (Tucker, 1968; House and Howell, 1992). Furthermore, charisma is a situated phenomenon based on follower perception. This means that what is considered charismatic in one organisational setting may not be deemed so in another (Conger and Kanungo, 1994). My definition of charisma for this thesis places the perception of the follower at its heart and I use the House and Baetz (1979) definition of charismatic leaders "leaders who by the force of their personal abilities are capable of having profound and extraordinary effects on followers". This makes the definition of charisma dependent on whether or not it delivers the change in follower commitment to the endeavour. It is therefore possible that the megascience project vision is the source of the 'profound and extraordinary effects' rather than the leader. This makes it legitimate to ask whether charisma is an important characteristic of leaders in a megascience project, which I will explore to address my first research question.

The traditional perspective of science as a unifying knowledge-seeking process may preclude transformational leadership within science (Merton, 1942). This could be because, by tradition, scientists are intrinsically motivated toward science, rendering a transformational leader seeking to inspire teams unnecessary (Merton, 1942). Megascience projects in particle physics generally construct apparatus to supply 'beam-time'[7] while separate experimental collaborations construct their own equipment for detecting and processing particle collision data. There are therefore two communities within particle physics, one an accelerator construction community and the other an experimental collaboration community. It is possible that senior accelerator leaders must

[7] 'Beamtime' is a period of experimenter access to the accelerator beam and can be considered a scarce resource that experimental collaborations must request.

act as transformational leaders to inspire greater confidence in themselves and their ability to deliver the project on time and on budget while experimental leaders might exhibit different characteristics and consult more widely on their plans, as the collaboration is a joint effort by many research laboratories. However, as stated above, it may be necessary to change leadership style in order to implement the vision (Hater and Bass, 1988; Kirkpatrick and Locke, 1996; Tracey and Hinkin, 1998). The literature referring to an individual as a transformational leader tends to be biographies (Rabi *et al.*, 1969; Wilson, 1970; Heilbron *et al.*, 1981b; Thorpe and Shapin, 2000). There appears to be a lack of academically rigorous studies focussing on leadership in megascience projects.

2.2.2 - Transactional leadership

Transactional leaders operate within an existing culture, contrasting with transformational leaders who seek to create or change organisations (Bass, 1990). They also use the prospect of reward to gain loyalty from subordinates and to drive agreements amongst employees and external stakeholders to achieve their aims (Bass, 1990). Transactional leaders use the principle of 'management by exception', whereby leadership intervention only occurs when team performance or behaviour drops below what the leader deems reasonable (Bass and Avolio, 1993).[8]

As will be revealed in Chapters 4, 5, and 6, megascience leaders may also act as transactional leaders when necessary. During negotiations between leaders and stakeholders for funding or political support, it may be appropriate for transactional leaders to ensure success by encouraging alignment within existing frameworks to ensure success. By contrast, a transformational leader is able to use the vision as a seductive tool to convince others to relinquish resources willingly (Bass, 1990). This was the experience of Smith (2007), a former Director General at CERN, who balanced the changing interests of differing stakeholder governments whilst also ensuring an approved budget proposal for the LHC. This is compatible with the Kirkpatrick and Locke (1996) theory that

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[8] There is a difference in terminology between transformational and transactional leadership, namely that transformational leaders have 'followers' as they gather followers organically, while transactional leaders have 'subordinates' because their authority is derived from the position they hold (Conger and Kanungo, 1994; Bass, 1990). This suggests that 'transactional leadership' is something of a tautology in that transactional leaders manage rather than lead. In other words, leaders stimulate change through the creation of a vision and aligning teams to overcome hurdles to realise this vision (Bass, 1990). By contrast, managers implement this leadership vision through the establishment of formalised plans and structures (Robbins, 2010). For convenience and clarity, this thesis refers to transactional leaders as such. I further discuss the difference between leadership and management in Chapters 4, 5 and 6.

implementing a transformational leadership vision requires a transition to a more transactional style. Equally, during the construction phase, a leader may choose not to intervene in the absence of any problem.

2.2.3 - Laissez-faire leadership

Laissez-faire leaders have a decentralised attitude towards decision making, which means that they generally allow the group dynamic to set organisational goals and timetables, permitting work to progress at its own pace with little intervention (Bass, 1990; Woods, 2004). Some authors have described laissez-faire leadership negatively, saying that such leaders *“avoid attempting to influence their subordinates and shirk their supervisory duties”* (Bradford and Lippitt, 1945; Bass, 1990). The use of 'shirk' by Bass (1990) suggests that he perceives that laissez-faire leadership arises from laziness and would seem to exclude the possibility that it could be an intentional strategy. This class of leadership has been claimed by many researchers to be both the least satisfying to subordinates and also the least effective leadership style, although Bass (1990) did not define ‘effective’ leadership. Apparent laissez-faire leadership may actually be a product of ‘management by exception’, where the leader only intervenes when performance deviates below acceptable levels, a component of transactional leadership considered in Section 2.2.2 above. This suggests that laissez-faire leadership is relatively ineffective in most projects; however, some studies have indicated that it can be appropriate in certain situations (Baumgartel, 1956; Andrews and Farris, 1967; Mumford *et al.*, 2002). One such situation might occur when the leader’s understanding is outdated or inadequate and a second situation might relate to an especially complex or creative venture, both posing challenges to a leader lacking the full breadth of necessary skills (Baumgartel, 1956; Andrews and Farris, 1967; Mumford *et al.*, 2002). In such situations, it has been suggested that a leader should receive appropriate advice from team members who are in a qualified position to comment on a particular matter (Baumgartel, 1956; Mumford *et al.*, 2002). This leadership style could have relevance to megascience projects as some of the technologies are developed in the course of application, so the technical competence of the leader may not necessary translate to a brand new technology. It might be advisable in such a scenario for the leader to empower the team to determine for itself how best to exploit such a new technology. The leader could then focus on justifying investment in the technology to the rest of the organisation.

2.2.4 - Authoritarian leadership

Authoritarian leadership, occasionally referred to in the literature as autocratic leadership, contrasts with laissez-faire leadership (Bass, 1990). The primary difference is that while laissez faire leadership decentralises decision making, authoritarian leadership centralises the decision making process, as well as requiring total obedience to the leader (Bass, 1990). Centralisation extends from decision making toward subordinates and "asserts absolute authority and control over subordinates and demands unquestionable obedience" (Cheng *et al.*, 2004). Despite the negative connotations of authoritarian leadership, it has been show to be effective in certain scenarios. These include a crisis where teams will abandon their autonomy to a leader who can make unpopular but necessary decisions to control a situation (Kidder, 1981; Taubes, 1986; De Mesquita and Siverson, 1995; Little and Grieco, 2003). While the literature usually associates authoritarian leadership with sole proprietorships, it can still be observed within large corporations such as Apple Inc.[9], where Steve Jobs took personal decisions over even trivial product design decisions. Jobs is perhaps the most well-known example of authoritarian leadership in both the academic literature and popular culture. While Jobs claimed technical competence in neither computer hardware or software design, his real skills were in marketing, aesthetic product design and extracting the best performance from others, and encouraging the creation of 'beautiful and elegant' products. This was a common theme throughout his career – according to Isaacson (2011), Jobs insisted that the original 1980s Macintosh should be "…as beautiful as possible, even if it's inside the box" (Isaacson, 2011; Isaacson, 2012). Jobs inspired his team by linking their design work to art, even extending this to encouraging them to sign the interior of the Macintosh case, a clear demonstration of charisma (Isaacson, 2011). Many individuals referred to his ability to extract the best out of his team and even present minor iterative advances as great leaps forward as the 'reality distortion field' (Isaacson, 2011; Sharma and Grant, 2011). Until the late 1990s, such authoritarian behaviour served to damage the prospects of his products, with a notable exception being the original Macintosh (Isaacson, 2011).[10] By the time of his 1997 return to Apple, although he still took direct control of key product decisions and occasionally

[9] The company was originally founded as Apple Computer, Inc. before being re-named Apple Inc. in 2007 to reflect a move into consumer electronics.

[10] One particular exception is Pixar, a company that originally made computer hardware for interpreting MRI scans and created cartoons as technical demonstrations. Jobs suggested shifting the company's focus from hardware to these cartoons, leaving it mostly alone to work as the creative team deemed most appropriate.

humiliated employees during product demonstrations, for the most part, Jobs' key decisions were successful. Jobs proved to be the saviour of Apple, taking necessary but occasionally unpopular decisions to shore up its financial position, pending the launch of a new product (Sharma and Grant, 2011). One example of the humiliation of employees occurred during the iPod project; Jobs desired an iPod of equivalent size to a pack of playing cards. The individual telling this story referred to Jobs seeing a prototype that did not meet this size brief – he threw the prototype into a nearby aquarium and said the bubbles clearly demonstrated empty space that could still be eliminated (Isaacson, 2011). Much of the scholarly literature does not treat authoritarian leadership positively; yet these examples above demonstrate the successful employment of authoritarian leadership. Some studies have proposed additional sub-dimensions to account for how some authoritarian leaders use rewards or punishments to induce compliance (Likert, 1977; Verma, 2014). These authors divide authoritarian leadership into punitive and benevolent sub-types (Likert, 1977). Punitive authoritarian leaders tend to be more forceful and use threats or punishments to retain their power and extract good performance (Likert, 1977). Benevolent authoritarian leaders, while also centralising decisions and demanding obedience, use the prospect of reward to incentivise relinquishing team autonomy (Likert, 1977).

In the case of megascience projects, it is questionable whether authoritarian leadership could be of value. As the scientists involved are likely to be intrinsically self-motivated, any leader granting insufficient autonomy could be perceived as demeaning (Law, 1994). However, it is also true that if a project were in a dangerous situation an authoritarian leader could take the necessary difficult decisions to bring it back on schedule or budget.

2.2.5 - Democratic leadership

According to the literature, democratic leaders set general strategy and articulate the values of inclusiveness, equal participation, and open debate while allowing followers to judge the most appropriate pathway to achieve goals (House, 1977; Bass, 1990; Gastil, 1994; Woods, 2004). The leader reserves the right to make necessary changes to ensure a successful outcome (Gastil, 1994). This is particularly frequent at the end of projects when disparate activities require close coordination (Gastil, 1994). Furthermore, unilateral decisions must be taken "extremely reluctant[ly]" and power must usually be equally distributed (Gastil, 1994). There is a debate in the literature over the exact definition of democratic leadership, further complicated by some literature associating it with methods of political governance (Gastil, 1994). In these political governance methods, democratic government is usually associated with periodic elections of representatives (Manin, 1997). Even in classical Greek direct democracy, there was an institution known as the Assembly, where all citizens could vote on decisions and elect officials (Thorley, 2005). The leadership literature characterises democratic leadership as occurring when the collective retains their power and the leader guides them through decision-making process, only occasionally taking unilateral decisions. This suggests that the leadership literature has interpreted democratic leadership using the classical direct definition (Bass, 1990).

In the case of megascience projects, it may be considered desirable for an authoritarian leader to exploit the rhetoric of democratic leadership to secure buy-in from team members before revealing the true nature of the leader (Gastil, 1994). An alternative perspective deems democratic leadership appropriate when innovative solutions are required and group consensus is desirable (Woods, 2004). Equally, if the leader has a degree of technical knowledge in the tasks, he/she can serve as a champion and facilitate discussions with team members (Woods, 2004).

Current literature has mostly discarded two of the categories of leadership, those of authoritarian and laissez-faire, and focusses instead on transformational and transactional leadership. The literature identifies laissez-faire and authoritarian leadership as two undesirable extremes, while transformational leadership is desirable with transactional leadership viewed as unavoidable to achieve the vision. This ignores the utility of the more extreme leadership styles. Such styles can be useful, particularly when the leader does not understand the underlying processes or needs to take necessary but unpopular decisions to bring a project under control.

2.3 - Evolutionary paradigm models

While the style paradigm models, which classify leadership into five categories, focus on leadership as a concept with leaders displaying discrete styles, the evolutionary paradigm models perceive leadership as a dynamic process (Bass, 1990; Virkus, 2009). The evolutionary paradigm begins from the premise that leaders are born to lead and there exist multiple methods of assessing how these leaders influence groups to meet their goals (Virkus, 2009; Northouse, 2015). These methods include trait, skills, style, skills, situational, and contingency theories (Virkus, 2009).

2.3.1 - Trait theory

Trait theory begins from the premise articulated by Galton (1869) that leadership is a unique property of extraordinary individuals who can be distinguished by their inherited or genetic makeup (Zaccaro, 2007). The identification of common traits amongst these extraordinary individuals makes it possible to identify and cultivate future leaders. Trait theory dominated the leadership research community for many years and identified a wide variety of leader traits. The most commonly identified traits were physical stature, self-confidence, sociability, persistence, and ambition (Cowley, 1928; Bird, 1940; Geier, 1967; Zaccaro, 2007).

There are weaknesses in this approach to the analysis of leadership. Firstly, while early work considered leadership traits to be permanent, subsequent analysis has led to the conclusion that traits are malleable and change over time (Galton, 1869; Hoffman *et al.*, 2011). This is reasonable, as it would be challenging to demonstrate fully formed leadership traits in childhood, as the original version of the theory suggested.

2.3.2 - Skills theory

The skills theory approach to leadership divides an organisation into multiple hierarchical levels, from junior positions to senior ones, with different levels of the organisation requiring skills in varying concentrations (Katz, 1974). Traits differ from skills in that traits describe what a person *is* but a skill is what a person can *do* (Virkus, 2009). Skills were classified by Katz (1974) into technical, human, and conceptual skills, which Mumford *et al.* (2007) described as the leadership skills strataplex. It is argued that, at lower levels of the organisation, technical and human skills are considered the most valuable, but at greater seniority one expects that technical and human skills tend to diminish considerably in importance while conceptual skills dominate (Katz, 1974). [11] The need for conceptual skills at senior levels is such that senior management team members could be selected simply to fill non-conceptual gaps in the leader's skillset (Katz, 1974).

The leadership skills strataplex is a popular concept with conceptual links to stratified systems theory, which also breaks down an organisation into three to five levels and theorises that as one progresses to more senior roles, increasingly greater importance is

[11] It should be noted that Katz (1974) claimed that technical skills diminished to very low levels of importance at a senior managerial level while human skills do not to the same extent.

attached to strategic skills than cognitive skills (Mumford *et al.*, 2007). A three-level model is most frequently used, which allows researchers to categorise work into specific problem-focussed teamwork, middle management, and corporate levels, although the literature usually describes them in terms of junior, mid, and senior levels (Mumford *et al.*, 2007). The concept of varying skills requirements would seem reasonable given that, as staff progress up the organisational structure, away from the technology and toward the corporate side, senior leaders take responsibility for charting the organisational trajectory (Katz, 1974). Although senior leaders in a megascience project will have oversight in the form of laboratory trustees or a governing council, they still have significant discretion in choosing how to implement strategy.

2.3.3 - Situational theory

Situational theory begins from the premise that there are multiple sources of power and these sources, or ‘power bases’, can be harnessed to legitimise the leader (Hersey *et al.*, 1988). It describes how these power bases can be managed to retain follower loyalty (Hersey *et al.*, 1988). This is an interesting concept, but there are some concerns about the validity of this approach concerning organisational culture. The idea of power bases implies internal conflict with a leader convincing or cajoling the bases into compliance. The value of situational theory is dependent on the culture of the organisation under investigation. If the organisation is going through internal change, this may be useful. The question of its applicability within megascience projects partly depends on whether science or the technology is the focus of the organisation. Some authors have claimed scientists have their own culture based on Mertonian norms (Merton, 1942). These norms are communalism, universalism, disinterestedness, originality, and organised scepticism (Merton, 1942). These are certainly high ideals to strive for but there is debate concerning the true nature of scientists involved in very large scientific projects.

Mitroff (1974) considered the case of the Apollo program and claimed to have discovered evidence of counter-norms in conflict with the Mertonian norms. These counter-norms were solitariness, particularism, interestedness, and dogmatism (Mitroff, 1974). Many of the scientists even argued that the Mertonian norms were naive (Mitroff, 1974). If decisions taken during a megascience project truly have the intention to advance science, then many decisions should be relatively straightforward, questioning the applicability of situational theory. However, if megascience project decisions seek to advance a given technology, internal conflicts over which technologies to use and personalities may dominate, forcing leaders to manage these conflicts. This context would make situational theory an appropriate tool for analysing the methods by which a leader influences teams to achieve their goals by managing these conflicts by playing one group (power base) off against another.

2.3.4 - Contingency theory

The fundamental premise of contingency theory is that the structure of a solution must be tailored to its situation if there is to be a successful outcome (Fiedler, 1964). When using contingency theory, an organisation uses a set of criteria to classify a leader. Equally, the situation can be classified according to a different set of criteria. This theory follows a 'best fit' rather than a 'best practice' model, implying that an appropriate leader should be matched to fit a particular situation (Galton, 1869; Fiedler, 1964). This is what I discovered was the strategy undertaken in megascience projects, which is discussed in Section 6.4. This conflicts with trait theory, where certain individuals are 'blessed' with leadership skills and context does not affect their chance of success (Galton, 1869).

Contingency theory describes a process of matching an appropriate leader to a given situation. The classification of leaders and situations according to the criteria outlined below creates the opportunity for a pairing process, which should lead to the optimal outcome. However, megascience projects last for many years with changing circumstances so multiple iterations of this process may be required as the situation changes. Below I review how the current literature proposes the classification process for a leader and a situation.

The most common method for assessing the leader is the Least Preferred Co-worker scale (also known as LPC), where the leader's level of task- and relationship- motivation is assessed (Fiedler *et al.*, 1976). It is possible to be both task- and relationship-motivated (Fiedler *et al*. 1976). Task-motivated leaders use the task outcome to determine group success, using incentives and punishments to adhere to plans with individual employees not a typical concern (Fiedler, 1964; Fiedler *et al.*, 1976). By contrast, relationship-motivated leaders facilitate interaction between team members on the assumption that internal knowledge exchange will create elegant solutions (Fiedler, 1964).

Likewise, Fiedler (1964) states that the situation is a key determinant of an appropriate style of leadership. Three key factors characterise the situation - leader-member relations, task structure, and position power (Fiedler, 1964).

Leader-member relations is one of the tools that can be used to classify the situation using situational theory; consider the general atmosphere of the group and attitudes toward the leader (Mumford *et al.*, 2000). Leaders who have good team relations are likely to have satisfied productive followers, while poor relations create an atmosphere of mutual hostility and poor performance (Wheeless *et al.*, 1984; Clampitt and Downs, 1993; Campbell *et al.*, 2003). Most leader-follower interactions will be to obtain information or to discuss social relations, referred to in Section 3.5.3 as transactional and interactional discourse respectively (Brown, 1983; McCarthy, 1991; Campbell *et al.*, 2003). But not all communications will be on an equal basis; the quality of the communications is determined according to Campbell *et al.* (2003) by the leader-member exchange between the two individuals.

Leader-member exchange (also known as LMX) expands on leader-member relations to include the relationship dynamic between the group of followers and the leader (Graen and Uhl-Bien, 1995). Graen and Uhl-Bien (1995) claimed that focussing on a single individual is short-sighted and ignores leader-follower interactions. Graen *et al.* (1982) characterised this exchange as a linear progression, starting with the offer to develop the leader-follower relationship. It was found that acceptance of this offer led to dramatic performance improvements (Graen *et al.*, 1982). Following this initial stage, participants are free to move to an acquaintance level, in which social interactions increase and shift a purely transactional discourse to include interactional components (Graen *et al.*, 1982). The final stage, although difficult to achieve but particularly beneficial, is ‘partnership’ where the leader and follower both feel the other will go beyond contractual requirements and have reciprocal influence. While the first two stages are desirable, it is questionable whether ‘partnership’ is desirable or even achievable. As this theory is over thirty years old, Graen *et al.* (1982) could also not have anticipated the growth of globalisation and the use of virtual teams, which have made it less likely that followers and their leader could develop the relationship that Graen *et al.* (1982) expected (Chidambaram, 1996). Virtual teams are considered in Section 2.4.4.

Task structure, a second tool for assessing the situation, is a measure of standardisation within work (Mott, 1971; Gillen and Carroll, 1985). A more standardised task with set procedures is less likely to suffer a schedule slippage, which suits a task-focussed leader who can expect certain minimum output levels (Pinto, 2012). Tasks with greater uncertainty are more suited to a relationship-motivated leader to promote a knowledge-sharing environment (Tosi and Tosi, 1976). As I discuss in Section 2.4, megascience projects appear to embody the characteristics of both technically uncertain projects and large projects, suggesting that there may be a low level of task structure and that leaders focus on facilitating knowledge sharing rather than schedules.

Position power is a third tool that can determine the nature of a situation. This is simply the powers that the leader has to reward or discipline team members. A leader with a wider range of powers has a greater positional power than one whose powers are less wide-ranging (Fiedler, 1964). An individual in a senior leadership position, such as a CEO, will have greater power to influence the direction of the organisation, but in some cases, it may take some time for the effects of such decisions to become apparent.

2.3.5 - Leadership and the project lifecycle

As I have discussed above, contingency theory has the idea of a 'pairing process' between leaders and a situation with multiple iterations as the situation changes (Fiedler, 1964; Fiedler *et al.*, 1976). There is some literature which considers how leadership might change over the course of a project life cycle (Gluck and Foster, 1975; Wheelwright, 1992). This provides an opportunity to consider contingency theory in practice. The needs of a project will inevitably change over its lifetime as the project moves from initial concept development until close-down and handover to operations or product launch (Adams and Barnd, 1983; King and Cleland, 1983; Turner, 1999; Turner and Müller, 2005). Although there are several potential models, the most frequently used is the four phase model where a project goes from concept through planning to execution and termination (See Table 2) (Adams and Barnd, 1983; King and Cleland, 1983; Pinto and Slevin, 1988). Project managers must be mindful and adjust their leadership style as necessary to meet the changing needs of the project (Frame, 1987; Wheelwright, 1992; Turner and Müller, 2005). Frame (1987) suggested that the leader starts the project with a laissez-faire style and becomes increasingly authoritarian as the project progresses. This shift in leadership style is necessary as the nature of the work changes from creating a concept design where a leader assists technical experts to delivering a project within reasonable parameters (Turner, 1999).

There are alternative models for the project lifecycle to account for particular types of work, most notably the product development lifecycle (Gluck and Foster, 1975; Wheelwright, 1992). This classifies the lifetime of product development from initial concept generation to final production. Although there is not consensus regarding how to sub-divide the activities into the phases (for example Wheelwright (1992) sub-divided design into basic design and prototype building) and there are some differences in the terminology, the broad phases are very similar (See Table 2 for a visual guide to mapping the lifecycles onto each other). Both Wheelwright (1992) and Gluck and Foster (1975) make the claim that management must spend a greater proportion of their time managing the development at its later stages even though their ability to influence the outcome is limited. I believe that this is similar to the authoritarian transition observed by Frame (1987). It must be noted that these works examined manufacturing and the technology industry rather than large projects; nonetheless it is possible that megascience projects likewise can be classified into phases each with shifting leadership requirements. One particular question is whether the megascience project lifecycle might map onto the project lifecycle or if it might fit into one of the development project lifecycles below in Table 2 given the shared technological nature. While both of these models suggest that each phase might last between six and nine months, it is rather more likely that it might last considerably longer in a large project such as a megascience project.

<table>
<tr><th>Project lifecycle</th><th>Wheelwright (1992) model</th><th>Gluck and Foster (1975) model</th></tr>
<tr><td>Conceptual</td><td>Knowledge acquisition</td><td>Study</td></tr>
<tr><td>Planning</td><td>Concept investigation</td><td rowspan="2">Design</td></tr>
<tr><td rowspan="3">Execution</td><td>Basic design</td></tr>
<tr><td>Prototype building</td><td>Development</td></tr>
<tr><td>Pilot production</td><td>Preproduction</td></tr>
<tr><td>Termination</td><td>Manufacturing ramp-up</td><td>Production</td></tr>
</table>

Table 2: A summary of the development project phases proposed by Wheelwright (1992) and Gluck and Foster (1975) respectively mapped onto the project lifecycle

As I have demonstrated in Sections 2.2 and 2.3, leadership is a phenomenon the study of which has interested many since the Victorian era. During this period of extensive study, there has been a transition from the evolutionary paradigm theories, wherein leaders are born to lead and academic discussion has mostly focussed on how these ‘great men’ influence others, toward the style paradigm models, where the focus is on the traits exhibited by such leaders. For the next phase of this literature review, in Section 2.4 I turn to the other body of literature that helps to inform this thesis – the project management literature. I primarily focus on the studies that are most pertinent to megascience projects.

2.4 - Project management literature

This section considers the relevant project management literature relating to megascience projects. Section 2.4.1 provides a definition of megascience that I used to determine the characteristics of such projects. Sections 2.4.2, 2.4.3, and 2.4.4 examine the characteristics of megascience projects in the light of the relevant literature.

A project has been defined as “an individual or collaborative enterprise that is carefully planned to achieve a particular aim” (Pinto, 2012). A project manager has a wide range of tracking tools available such as Work Breakdown Structures, a process in which project objectives are broken down into smaller more specific tasks; PERT, which allocates time to individual tasks; and Risk Impact Matrices, a visual method of identifying and categorising risks (Pinto, 2012).

2.4.1 - Definition of megascience

Drawing on the literature on megascience in this section, the definition of megascience applied to this thesis is *large-scale laboratories undertaking experiments or other projects in the billion US dollar range with no formally defined upper boundary*. The lack of an upper boundary is due to a cycle by which scientific questions arise from new data, which lead to proposals for new experiments, which can require upgrades to the project to enhance beam luminosity, beam energy or other factors. This thesis will consider that the successful endpoint of a megascience projects occurs when both experimentation and all upgrades are complete. The focus then changes to a new subset of science which necessitates the construction of new apparatus.

I have used this definition to help guide me to the appropriate project management literature. There are other more practical concerns regarding this definition that became evident during the research design; these concerns are considered in more detail in Section 3.2.

2.4.2 - Characteristics of megascience projects

In the following sections, I identify the characteristics of megascience projects. These characteristics can be found in other project types, but the existence of these characteristics in a project of this scale justifies the novelty of megascience projects as a subcategory of large projects and my decision to investigate them in this thesis.

Thus far, I have outlined the general characteristics of projects. However, megascience projects seem to be a subcategory of large projects that possess the novel factor of a high or very high level of technological uncertainty that mark them out from other large projects. I shall firstly examine the primary characteristic that makes megascience projects slightly different from other large projects, namely the level of technological uncertainty.

2.4.3 - Technological uncertainty within projects

Many projects can be managed using standardised methodologies which can be found in bodies of knowledge, both internally held by the organisation and externally in databases (Pinto, 2012). These standardised methodologies can inform a project manager about matters concerning organising, scheduling, and budgeting of these projects (Pinto, 2012). However, more innovative projects may require greater tolerance towards budget or schedule changes as novel solutions may need to be devised for unanticipated challenges (Shenhar, 1993).

Some authors have claimed that innovative projects reduce the utility of established bodies of knowledge (Shenhar and Dvir, 1996; Pich *et al.*, 2002). While these bodies of knowledge can be useful for managing projects with well-understood technological issues, when projects exhibit a certain level of technological uncertainty, the application of project management techniques based on standardised methodologies needs to be re-examined. This examination is based on the acknowledgement that these new uncertainties bring into question fixed timetables and freezing a design at an early stage (McFarlan, 1981; Shenhar and Dvir, 1996).

Shenhar and Dvir (1996) proposed a classification system for such projects based on the associated technological uncertainty. This varies from a class ‘A’ project that utilises existing technology in familiar ways to class ‘D’ projects in which new technologies are developed in the course of application (See Table 3).

Classification of Project	Technological Uncertainty Level	Description	Example
A	Low	Familiar technology used in familiar ways	Bridge[12]
B	Medium	Adaptation of familiar technology possibly incorporating new features	Mobile phone
C	High	First use of new technologies that already exist	Space Shuttle
D	Super High	Development of new technology in the context of application	Apollo Program

Table 3: The project technological uncertainty classification system proposed by Shenhar and Dvir (1996)

As Shenhar and Dvir (1996) considered both the Space Shuttle and Apollo Programs to be highly uncertain projects, it seems reasonable to assume that megascience projects possess a similar level of technological uncertainty. One must also consider that some projects meeting the definition of megascience projects outlined in Section 2.4.1, have been described as requiring the use of bespoke new technologies, or the use of new technologies on an unusually large scale (Tollestrup, 1996; Wyss, 2000). However, Shenhar and Dvir (1996) did not account for the breadth of activities that may be encompassed in a project. While a class 'D' project may be considered to have a very high level of technological uncertainty overall, there are likely to be activities within the project that are more technologically certain.

Overlooking the granularity of task uncertainty within the project may lead to an unjustifiably relaxed attitude regarding cost overruns and design changes. This was true in the case of the Channel Tunnel, a railway tunnel under the English Channel (Kirkland, 1995; Genus, 1997). While most infrastructure projects are considered to be class 'A' projects using Shenhar and Dvir's (1996) classification system of technological uncertainty, the length as well as the undersea nature of the Channel Tunnel justifies it as a class 'B' or even class 'C' project. While there were some technical challenges, which

[12] This is a generalisation, as some bridges historically have had a certain degree of technological uncertainty eg. the first steel bridge and the first major suspension bridge. However, bridges built today generally possess a low technological uncertainty, as noted by Shenhar and Dvir (1996).

necessitated a greater tolerance of delays on the French side, there was scope to reduce costs in areas of the project with greater technological certainty (Kirkland, 1995). This has been attributed to the lack of a coordinating structure above the two separate British and French consortia (Kirkland, 1995; Genus, 1997). This lack of coordination caused issues such as the use of differing specifications for rolling stock, tunnel shielding, surface building architects, and even fonts on signage between the UK and France (Kirkland, 1995). Interestingly Vickerman (1994) stated that the lack of a project 'champion' able to exercise both political and financial power over a previous attempt to build a Channel Tunnel was a major factor in its eventual collapse. This further justifies investigating leadership in megascience projects as the lack of such a champion could result in a project failure.

The Government Code and Cypher School at Bletchley Park during the Second World War provides a contrast. Grey (2012) claimed that two parallel cultures developed within Bletchley Park during this time. The first was a small meritocratic inner circle of highly skilled decrypters and the second was a much larger secure message service (Grey, 2012). Amongst the decrypters the atmosphere was "that of a senior member of a common room" (Grey, 2012). This indicates an informal hierarchy with leaders taking a consultative role, similar to an academic environment. It is also documented that many projects similar to megascience projects such as the Manhattan Project sought to create a similar work environment (Hoddeson, 1992; Hughes, 1998; Hughes, 2004; Lenfle and Loch, 2010).

However, amongst more routine work there were certainly grounds to claim a Taylorist approach was used (Weber, 2009). The Typex pool, wherein secure messages were encoded, was a suitable situation to apply Weber's theory of bureaucratic management, which is appropriate for standardised tasks where management can prioritise speed and precision (Weber, 2009; Grey, 2012). This can be implemented with the relatively standardised work conducted in the Typex pool, where typists typed out secure messages on specific Typex cipher machines, but the same is not true for tasks with a higher degree of uncertainty such as decryption work. This all correlates with Shenhar and Dvir's (1996) work, considered earlier on the subject of technological uncertainty in a non-technological context if one sub-divides a project into activities and considers Typex work as a class 'A' type activity and the decryption work as a class 'C' or class 'D' class activity (Shenhar and Dvir, 1996).

2.4.4 - Large Projects

Although the project management literature offers lessons on how to organise and track a project, a relatively recent development has been the budgets of projects frequently reaching at least one billion US dollars. These projects are often referred to as megaprojects; those authors have used the one billion US dollar figure as the point where a project becomes a megaproject, although this lower boundary has not been formalised (Davies *et al.*, 2009). The idea that a 'teraproject' sometime in the future might cost one trillion US dollars has even been suggested (Flyvbjerg, 2014). I chose to avoid the potential for confusion between 'megaprojects' and 'megascience projects', and so I have referred to the 'large project' body of literature here. I refer to large projects as those with an extremely large budget usually in the billions of US dollars (Flyvbjerg *et al.*, 2003). Many of these large projects have been devised to provide infrastructure and there tends to be heavy involvement from governments at all levels (Flyvbjerg *et al.*, 2003). They are often undertaken on the basis of promoting economic or social benefits nationally or internationally (Flyvbjerg *et al.*, 2003). Examples of large projects include the Channel Tunnel, the Oresund Bridge[13], and the proposed High Speed 2 railway.[14]

Generally, large projects today are organised along a client and delivery partner arrangement (Davies, 2017). The client, which can be an organisation or a government, defines the goals and specifications of the systems to be constructed and invites bids for the contract (Davies and Mackenzie, 2014). Any organisation may make a bid, although a common occurrence is that several organisations pool their resources to form a joint venture that makes a bid to be the delivery partner (Davies, 2017). From amongst these bids, the delivery partner responsible for meeting the client's brief is selected. However, in most large projects, the client usually lacks the technical understanding to create detailed specific technical designs before submitting for tender (Davies and Mackenzie, 2014). Likewise, as I noted in Section 2.1.2, most clients lack the understanding to account for how the various systems within the project array will interface. Leaders in megascience projects often focus on how these technological systems interface,

[13] The Oresund Bridge links Denmark and Sweden across the Oresund strait. Although it is often referred to solely as a bridge, for commercial reasons it includes a tunnel. Its cost was approximately 2.6 billion Euros and it opened in 2000.

[14] The High Speed 2 railway (often referred to as HS2) is a proposed high speed railway line in the United Kingdom. The current design is expected to link major cities in the north of England, constituting a major upgrade of rail speed and capacity. Although there is currently debate over the expected final cost of the railway, it is anticipated that the costs will be in the tens of billions of pounds range.

underlining the status of megascience projects as a relatively unusual subcategory within large projects (Davies and Mackenzie, 2014; Evans, 2014). In other large projects, many clients seek to create the space for the delivery partner to design and make technical decisions (Davies and Mackenzie, 2014). Another unusual characteristic of megascience projects is that the machine is generally assembled by laboratory employees who occasionally have to ‘repair’ equipment that does not meet the very tight specifications (CERN, 2008). This emphasis on understanding the technology is another factor that may explain why scientific project leaders are selected from within science rather than brought in from the ranks of professional project managers.

Megascience projects are a subcategory of large projects with some additional characteristics such as their high level of technological uncertainty (McFarlan, 1981; Flyvbjerg *et al.*, 2003). All large projects generally share certain additional characteristics that differentiate them from other projects (Mersino, 2007). According to Mersino (2007), these key characteristics also include the use of subcontractors, virtual teams and the level of importance to the organisation.

It is unusual for a single organisation to be able to produce all of the components for a large project within a reasonable timescale (Miller and Lessard, 2001). Therefore large projects incorporate subcontractors to take advantage of economies of scale and technical competencies offered by external actors (Brooks *et al.*, 1979). In the case of megascience projects, these subcontractors can be in private industry or even other laboratories (Tollestrup, 1996; Wyss, 2000). Managing the risk that subcontractors might not produce parts meeting specifications is a great challenge, and the literature indicates that external vendor relationships should be based on mutual honesty and openness (Irvine and Martin, 1984; Martin and Irvine, 1984a; Martin and Irvine, 1984b). This could involve creating clear specifications for components, regular meetings to ensure that the contractor was performing adequately, and testing these components in an environment wherein a test failure cannot damage other components (Krige, 1997).

Virtual teams are created when team members are separated by significant geographic distance, necessitating the use of technology for communication, as opposed to face-to-face teams where team members are much closer together (Warkentin *et al.*, 1997; Mersino, 2007). In the case of megascience projects, virtual teams could consist of experimental collaborations, constructing parts of a detector at many different universities or perhaps a committee working remotely from the laboratory (Beaver, 1986).

However, with distance comes the need for technological solutions to solve communication challenges (Warkentin *et al.*, 1997). Research has traditionally indicated that, due to poor relational links between members, virtual teams suffer from poor communications (Kinney and Panko, 1996). But much of this research investigated too short a time span to observe the evolution of team dynamics (Warkentin *et al.*, 1997). Chidambaram (1996) argued that virtual teams should be able to overcome technological limitations and achieve the same performance levels as face-to-face groups, but this process occurs over a much longer timescale because the technology forces a reduction in social information sharing. As some scientific experimental collaborations, using accelerators constructed during megascience projects, exist for a decade or more, collaborators should also be able to overcome the communication issues associated with virtual teams, with the collaborations choosing to encourage many members to visit the central hub of the experiment.

Most organisations will closely supervise contractors and project managers to ensure that the project is progressing according to the timeline and expected budget (Floricel and Miller, 2001). Another characteristic of large projects is the high level of investment over a long time (Stannard, 1990; Flyvbjerg *et al.*, 2003; Mersino, 2007). The labour and capital investment required to complete a project could strain on activities elsewhere in an organisation. For example the LHC, which dominated the CERN budget to such an extent that at one point the entire CERN accelerator system had to be shut for several months to make necessary savings (Hobday, 1998; Hobday, 2000). It can then be difficult to curtail the project as cutbacks will have a disproportionate effect; for example, cutting the budget for a single year can cause a delay of several years (Smith, 2007).

The scale of large projects often makes government a substantial stakeholder. These governments may have their own agendas that could take precedence over the project. For example, during the project to construct the Concorde supersonic transport, some authors have claimed that the British and French governments each had a separate agenda (Davis, 1969; May, 1979). The British government saw Concorde as a means to secure membership of the European Economic Community while the French government saw Concorde as a way to stay competitive with American aerospace companies while sharing costs (Davis, 1969; May, 1979). The final Concorde product was a huge commercial failure - the 1970s oil crisis caused many prospective customers to cancel their orders and eventually only the respective national carriers purchased planes for a token sum (Davis, 1969; Wilson, 1973; May, 1979; Orlebar, 2004).

Although the plane was eventually taken out of service in 2003, the reality was that it was running a token service throughout the majority of its lifespan. This primarily involved two daily return services from London Heathrow to New York's JFK airport and Paris to JFK with a single weekly winter service to Barbados.[15] These services were a prestige service and although neither British Airways nor Air France released public accounts on Concorde services, it was generally thought that these services were not particularly profitable (Scotchmer, 2004). The plane was always going to be taken out of service once parts became difficult to source, with some Concordes cannibalised to provide parts for those still in service (Duffey and Saull, 2008). While other events affected Concorde, such as the 2000 Gonesse crash and the post-September 11th downturn, these perhaps only served to hasten the inevitable retirement of the plane (Trubshaw, 2001; Orlebar, 2004).

However, it could be argued that the government agendas I described above formed the 'true' goals of the Concorde project – an argument with which I agree (May, 1979). If one considers these the real goals of Concorde, with commercial performance being largely irrelevant, then one could cite the subsequent British entry to the European Economic Community and the creation of Airbus with a substantial French presence, as evidence of its success (Davis, 1969; May, 1979; Orlebar, 2004). This analysis of the Concorde project demonstrates that a project can also include unexpected objectives, designed to advance government agendas, and the project is a mere conduit to improve relations.

2.4.5 - Summary of the characteristics of megascience projects

In this section, I summarise the characteristics of megascience projects as a subcategory of large projects. According to Shenhar and Dvir (1996), when a project displays a minimum level of technological uncertainty, leaders may have to take alternative attitudes

[15] Upon entering service, Air France and British Airways operated Concorde from Paris to Rio de Janeiro via Dakar and from London to Bahrain respectively. The airlines also experimented with other destinations such as Mexico City, Miami, Singapore, and Washington DC. However, for the majority of its lifetime, Concorde mainly ran on the transatlantic route between London/Paris and New York.

regarding cost overruns and the final project design. This is because some aspects of the project involve the first use of technologies in a given field or technologies developed in the context of application (Shenhar and Dvir, 1996).

The literature also regards large projects as displaying certain common characteristics. These are:–

- the use of subcontractors;
- virtual teams;
- the level of importance to the organisation and stakeholders.

As discussed above, megascience projects are a subcategory of large projects which incorporate the technologically uncertain project literature. This is unusual in that most large projects employ established engineering methods and mechanisms to achieve project success. This would categorise most traditional large projects as class ‘A’ or class ‘B’ projects using the Shenhar and Dvir (1996) classification. But megascience projects use novel technical techniques, often being implemented for the first time, making them class ‘C’ or even class ‘D’ projects. The addition of the technological uncertainty issue makes megascience projects novel and worthy of investigation to determine whether leadership manifests itself in a new way or is similar to that in other large projects.

2.5 - Other relevant bodies of literature

During my literature search, I found other bodies of literature relating to large complex projects that provided useful additional insights for this thesis. However, these bodies were insufficiently relevant to constitute key components of this thesis. Nonetheless, they helped to highlight the rationale for my choice in technologically uncertain projects.

2.5.1 - Complex product systems (CoPS)

Complex product systems (CoPS) are high-value high-technology goods usually made on a one-of-a-kind or small batch basis (Davies and Brady, 2000). The CoPS literature emerged during the middle of the 1990s. Tidd (1995) first used the term in the context of home automation but it only began to emerge as a body of literature in its own right towards the end of that decade (Hobday, 1998; Hobday and Rush, 1999). This body of literature is relatively limited compared with the body of large project management reviewed above. Nonetheless it is closely related to the large project literature as it has examined large projects such as the A380 aircraft (Dorfler and Baumann, 2014). There has also been a CoPS investigation of CERN, a major particle physics laboratory, but this was in terms of change management (Whyte *et al.*, 2016). The CoPS literature tends to focus on learning from specific challenges that emerge during a project rather than the entire project lifecycle, on which this thesis focusses. It is also clear that the CoPS literature has had an effect on the large project literature, particularly on the subject of innovation within such projects. However, this thesis focusses on leadership rather than innovation; therefore, it is appropriate to direct this thesis toward the relevant large and technologically uncertain project management literature rather than CoPS.

2.5.2 - Sociotechnical systems (STS) and large technical systems (LTS)

The concept of a sociotechnical system emerged after observations of British miners found instances of highly successful teams within a large organisation who had for the most part rejected post-war mechanisation (Trist and Bamforth, 1951; Fox, 1995). These complex systems are composed of social and technical components which must be considered as interdependent and complementary (Fox, 1995). In this way, the social component can re-inforce the technical component and vice versa. The technical side of the system includes the working conditions, the degree of task mechanisation, and the identification and allocation of resources to complete goals (Trist and Bamforth, 1951). The social dimension generally includes analysis of the work organisation with a particular importance attached to control and coordination (Emery, 1987).

Related to the concept of sociotechnical systems is the notion of 'large technical systems' (Hughes, 1987). These large technical systems are constructed by social interactions and can shape the wider society (Hughes, 1987). A single system is composed of components which may be physical artefacts or non-physical in nature (Geyer and Davies, 2000). These components interact with one another in a particular configuration, and these interactions often result in a single change forcing further changes elsewhere in the system (Hughes, 1987; Geyer and Davies, 2000). These systems are limited by controls either from physical artefacts or human operators (Hughes, 1987). However, Hughes (1987) incorporates external political and social elements into these systems, while the concept of sociotechnical systems does not.

Such large technical systems include the USS Nautilus (the first nuclear powered submarine), the ARPANET (an early version of the internet), and the Boston Central

Artery/Tunnel project (Hughes, 1998; Hughes, 2004).[16] However, for the purposes of this thesis I will focus on two important large technical systems to identify what systems builders are and how they operate - the SAGE air defence project and the Atlas intercontinental ballistic missile project.

Both the SAGE project and the Atlas project occurred during the first phase of the Cold War before détente (Hughes, 1998). However, while the SAGE project began at a very early stage in the Cold War and many of the project management tools had yet to be developed, the Atlas project occurred during a very tense period of the Cold War when there had already been substantial investment into project management (Morris, 2013). The SAGE project (formally known as the Semi-Automatic Ground Environment) was an air defence system that used a combination of computers and radar to plot the course of an incoming plane or missile. Previously, air defence systems used radar to identify the coordinates of a plane with the course plotted on a physical map by trained operators. This was sufficient for plotting propeller planes during the Second World War but the associated inefficiencies might have led to unacceptable delays when plotting a jet-powered plane. SAGE automatically plotted these coordinates and update them in real-time. Although computer prototypes existed which worked on a small scale, the challenge was to expand this system to work on a continental scale. The Massachusetts Institute of Technology (MIT) chose to confront this challenge by creating a new laboratory dedicated to solving air defence issues using electronics. MIT had extensive expertise in electronic research and radar as separate disciplines, so their choice to create a laboratory synthesising their twin competencies proved successful (Hughes, 1998). In this case, Hughes (1998) characterises MIT as the systems builder for creating this laboratory dedicated to air defence work, thus demonstrating that it is possible for an organisation to be a systems builder.

The Atlas project was the effort to build the first American Intercontinental Ballistic Missile (ICBM), which is considered a significant development in the field of systems engineering (Morris, 2013). Although withdrawn from military service after a relatively short period, the leftover units were recycled for civilian rocket launches as the Americans scrambled to develop their space programme after the Soviet launch of Sputnik (Brooks *et al.*, 1979). Therefore, one might argue that its real value was as a learning exercise for

[16] Often referred to colloquially as the ‘Big Dig’.

project managers in how to manage the construction of a large technical system. The organisation of such an effort proved a challenge equal to the technical issues (Hughes, 1998). One prominent committee recommended the creation of a new independent management organisation, staffed by the most technically competent scientists. This is highly significant for my research, as megascience projects are led by scientists whereas other large projects generally turn to professional project managers to organise the effort. Hughes (1998) identified two individuals as systems builders during the Atlas project – Bernard Schriever and Simon Ramo. While neither are characterised as 'heroic systems builders' who made all of the technical decisions, they both maintained a focus on the project and their teams while refusing to give into political pressure when it would have impeded their teams (Hughes, 1998).

Hughes (1998) characterises a systems builder as an individual or organisation in charge of a technological project from beginning to the end, crossing disciplinary and boundaries as necessary. However according to Hughes (1998), rather than making detailed technical choices, a systems builder focusses on the interfaces between components to ensure that the final product will run smoothly. It is also noted that these 'system builders' and "…are like 'heterogeneous engineers'" (Hughes, 1987; Law, 1987b). This links with the conceptual framework chosen for this thesis, the heterogeneous engineer, discussed below in Section 2.7.3.

2.6 - Research questions

During the literature review, it became apparent that a substantial gap in the literature exists. While there are many accounts of leadership in projects that could feasibly be a technologically uncertain, there have been very few attempts to investigate leadership of large projects (Kidder, 1981; Arain, 2012; Dimitriou *et al.*, 2014; Olaniran *et al.*, 2015). Studies that have considered leadership in large projects have attempted to build theory from a single case, making it impossible to differentiate from what is unique from a single project and what may be common to all large projects (Arain, 2012; Olaniran *et al.*, 2015). However, these studies do contribute to knowledge in the field of leadership in large projects and act as a starting point for this research. Equally, I could identify no information regarding leadership development schemes existing in large projects. This lack of such understanding offers the possibility that leadership in megascience projects can be considered a synthesis of the styles observed in both technologically uncertain and large projects. My definition of megascience will be utilised to achieve the aim of this thesis, which is to answer the following questions:

1. What are the characteristics of those who lead megascience projects?

2. Where were their leadership skills developed?

3. How were their leadership skills developed?

2.7 - Conceptual framework

It has become clear that there is a gap in existing knowledge concerning the leadership characteristics of those leading megascience projects. As noted above, megascience projects appear to be a subcategory of large projects that incorporate a 'high' or 'super high' level of technological uncertainty (Shenhar and Dvir, 1996). However, they do not share the characteristic of many large projects that they act to enable economic growth, but rather serve to generate new scientific knowledge (Geyer and Davies, 2000; Flyvbjerg *et al.*, 2003).

Furthermore, I identified in Sections 2.2, 2.3, and 2.4 that in neither the leadership nor the project management literature does there appear to be much research conducted into the leadership characteristics of those who lead megascience projects, although as noted earlier there is some work looking at experimental collaborations (Liyanage and Boisot, 2011). While some studies have considered leadership in large projects, these have mostly attempted to build theory based on a single case (Arain, 2012; Dimitriou *et al.*, 2014). Although there is a great deal of research into leadership, such research has tended to focus on a single charismatic individual from whom generalisations have been made rather than gathering a larger body of evidence (Irvine and Martin, 1984; Martin and Irvine, 1984a; Martin and Irvine, 1984b; Krige, 2001; Traweek, 2009; Zabusky, 2011). Significantly, other studies concentrating on a single laboratory have come close to examining which leadership style or characteristics might be conducive to megascience projects, but have not elaborated beyond stating the importance of a good 'fit' between leader and project (Krige, 1997).

In the section below, I discuss the two potential theoretical frameworks before selecting what appears to be the most suitable one for this thesis. This concept is the heterogeneous engineer (Krige, 2001).

2.7.1 - Considered conceptual frameworks

In order to investigate the phenomenon of leadership within these megascience projects, it was necessary to find an appropriate construct that I could use to interpret my findings. The literature suggests that a combination of scientific and leadership skills is required both to create scientific credibility and to inspire team members (Rabi *et al.*, 1969; Wilson, 1970; Heilbron *et al.*, 1981b; Seidel, 1983; Thorpe and Shapin, 2000; Krige, 2001; Hughes, 2002; Smith, 2007; Hoddeson *et al.*, 2008). A suitable conceptual framework for this thesis would allow the freedom to incorporate this combination of skillsets.

2.7.2 - The R&D leader

The concept of the R&D leader was developed by Elkins and Keller (2003) after observing the under-investigation of leaders in a variety of R&D departments. According to Narayanan (2000), research and development require more lead time and produce sporadic output compared to more traditional commercial activities such as marketing or finance (Elkins and Keller, 2003). This makes R&D at least partially similar to science as both have a degree of isolation from other sectors of the business to allow for proper cultivation of the new product (Narayanan, 2000). In R&D, many leaders are selected based on technical competence rather than leadership abilities in a similar way to science, where leaders can emerge based on their scientific prowess (Narayanan, 2000; Elkins and Keller, 2003).

However, I have a concern that many authors have grouped R&D together when the reality is that these are two very different processes. The first, research, is a very open process where teams or individuals work to discover and select a single prospect to develop. The second process, development, is where a team or individual takes this single prospect and put it through an increasingly constrained set of parameters to turn the single prospect into a final product that can receive regulatory approval. These substantial differences make it rather unlikely that any single team or even single leader will guide a product through both the research and development phases. The proposed framework for the R&D leader identifies four categories (Elkins and Keller, 2003). These are teams, environmental factors, leader behaviours and roles, and skills and research topics. A suitable foundation must consider all these factors if reliable theory is to be developed.

Firstly, the team component of the R&D leader conceptual framework examines the composition, selection, and formation of teams. One of the key concerns when selecting a team is that they will be receptive to the vision (Elkins and Keller, 2003). This vision will create a common identity within the interdisciplinary team and encourage them to work together to bring the new product to market (Elkins and Keller, 2003). Elkins and Keller (2003) believed that transformational leadership was highly appropriate amongst such teams as it would encourage a good leader-member exchange between the leader and the team. As I discuss in Section 2.3.4, leader-member exchange describes the state of relations between the leader and the team (Graen *et al.*, 1982; Graen and Uhl-Bien, 1995). It is characterised as a linear progression where there are greater levels of information exchange as the relations improve (Graen *et al.*, 1982). However, Elkins and Keller (2003) noted that it was unlikely that leader-member exchange will be uniform across an entire team, and theorised that the type of R&D project would become a variable governing the quality of leader-member exchange. Development projects, which generally involve a relatively standardised process where researchers put a promising product through a series of increasingly stringent tests, are associated with higher quality leader-member exchange (Elkins and Keller, 2003).

The second category of 'leader behaviour and roles' uses the leader as the unit of analysis. It examines the extent to which the leader can cross boundaries both within the organisation and in the wider business environment to gather the necessary resources to allow the team to perform. Within the organisation, the leader can act as project champion across boundaries by gaining the support of other departments such as marketing (Elkins and Keller, 2003). Another way that a leader can cross internal boundaries to generate support for the project is to lobby senior management directly. In terms of the wider business environment, leaders can cross boundaries by building up relationships with suppliers, customers, and regulatory agencies (Elkins and Keller, 2003). Several authors have associated boundary-spanning leaders with higher levels of support across the organisation and a greater likelihood of project success (Markham *et al.*, 1991; Waldman and Atwater, 1994).

It is here where the third category, that of 'environmental factors' becomes relevant. This relates to the external business environment that will affect organisational performance in the marketplace. Elkins and Keller (2003) identified that new technologies, changing product lifecycles, or even wider changes in the industry could affect leadership. In the case of megascience projects, these might be changes in the funding environment, or new knowledge obtained elsewhere that could promote or hinder the building of new apparatus to exploit new science.

The final category, which was referred to by Elkins and Keller (2003) as ‘skills and research topics’, examines the leader and team using other existing leadership theories such as style, leader-member exchange and contingency theory (Fiedler, 1964; Bass, 1990; Graen and Uhl-Bien, 1995). These were considered in Sections 2.2 and 2.3.4 respectively.

2.7.3 - The heterogeneous engineer

The concept of the heterogeneous engineer is derived from heterogeneous engineering, a social explanation of technical change (Law, 1987a). During the late 15th and early 16th Centuries, Portugal, due to the domination of overland trade routes by foreign powers, shifted its naval focus from the Mediterranean to the open ocean (Law, 1987a). Law (1987a) described the Portuguese ships as systems, made up of both material and human experiences. These systems would minimise the risk of disassociation by external actors (Law, 1987a). Prior to this Portuguese expansion, most European naval technology was designed for the relatively calm and sheltered waters of the Mediterranean (Law, 1987a). When Portugal sought to explore the West African coast, it found its ships inadequate as their human experiences to date were unsuitable for these new external actors (Law, 1987a). The first deficiency was the method of propulsion, namely oar power, a highly labour-intensive method that sufficed for the Mediterranean but was insufficient for an ocean-going vessel. Secondly, their present navigational tools and methods were unsuitable for traversing the Atlantic and Indian oceans. These two challenges were resolved by redesigning the ship to incorporate new sails, and developing new navigational technologies and human experiences led to the discovery of safer routes (Law, 1987a). These new ship systems proved adaptable when new unexpected actors emerged (Law, 1987a). This was illustrated when, having already built a system sufficiently advanced to round the Cape of Good Hope, Portuguese ships encountered hostile forces in the Arabian Peninsula (Law, 1987a). At that time the Portuguese fleet had not previously encountered serious opposition but were able to retro-fit cannons to counter this new threat (Law, 1987a).

Krige (2001) theorised that a heterogeneous engineer likewise brings together the necessary technological, human, material, and financial resources to achieve scientific discoveries. The novel component of Krige's (2001) paper was to expand on Law's (1987b) and Hughes' (1987) brief statements and transfer the concept of heterogeneous engineering from a systems-based perspective to a personified concept in which an individual is able to bring together both their own knowledge and the technical, political, and financial support to ensure a successful outcome.

This was considered in the case of Carlo Rubbia's award of the 1984 Nobel Prize for physics for his role in the discovery of the W and Z bosons, which mediate the weak nuclear force (Arnison *et al.*, 1983; Banner *et al.*, 1983; Krige, 2001).[17] The awarding committee noted that a marriage of his knowledge and enthusiasm was what convinced the CERN management that such a project could be accomplished (Krige, 2001). The committee also noted he was responsible for building a team of scientists to implement the project. There were five primary criteria that made Rubbia's project as important within the scientific community as the Manhattan Project (Krige, 2001). These were a clearly defined physics objective, technological innovation, the acquisition and management of human and material resources, unwavering buy-in from laboratory management, and that it could strike a new balance in scientific power between the United States and Europe (Krige, 2001).

During the 1970s, physicists investigated the nature of colliding beam accelerators in which two hadron beams orbit in opposite directions to allow higher energy collisions (Hoddeson *et al.*, 2008).[18] Several laboratories that had an interest in these colliding beams devised experiments to test their technical feasibility (Krige, 2001; Hoddeson *et al.*, 2008). The first hadron collider constructed at CERN, ISR, collided two beams of protons at approximately 62GeV (Krige *et al.*, 1997). ISR had the potential to make many new discoveries, but design limitations effectively forced physicists to use it as a proving ground for technologies and methods to improve the beam quality in future colliders (Krige *et al.*, 1997). Two possible methods existed to improve the luminosity of a hadron beam, electron cooling and stochastic cooling, with experiments conducted in the Soviet

[17] Krige (2001) also briefly mentions Charles Draper of the MIT Instrumentation Laboratory as a heterogeneous engineer, but the topic of the paper is clearly Carlo Rubbia.

[18] Previously physicists made use of fixed-target hadron colliders, where a single beam collides with a static target. It should be noted that lepton colliders had been operating ten years before ISR.

Union and at CERN respectively (Krige, 2001). Carlo Rubbia was part of a collaboration that proposed to Fermilab the idea of incorporating these cooling methods to collide particles and antiparticles, a proposal was rejected as “premature” (Rubbia *et al.*, 1977; Rubbia, 1985; Krige, 2001). This collaboration was later invited by CERN to conduct their work at the SPS (Krige, 2001). CERN wished to reverse a trend whereby their lack of audacity had resulted in CERN making few discoveries, while Fermilab’s comfort with audacious statements had paid off with several discoveries and awards (Irvine and Martin, 1984; Martin and Irvine, 1984a; Martin and Irvine, 1984b; Krige *et al.*, 1997; Krige, 2001). These two laboratories developed at a similar time and this fostered a sense of rivalry (Lederman, 1983; Krige, 2001; Hoddeson *et al.*, 2008).

Rubbia took a significant role in the effort at CERN and began to display the behaviours Krige (2001) associated with the heterogeneous engineer. Firstly, Rubbia secured buy-in from senior figures by arguing that success would bring acclaim to CERN (Krige, 2001). Secondly, he was able to create a more risk-favourable environment at CERN and rapidly mobilised the necessary human resources to ensure a unified endeavour (Krige, 2001). Thirdly, rapid approval of finance was secured by exploiting a loophole within the CERN framework – new accelerators require consultation and special funding from member states while experiments do not (Krige, 2001). Rubbia successfully argued that the proposed accelerator infrastructure changes were part of an experiment which allowed the funding to come from the annual operating budget without consulting the member states (Krige, 2001). In this way, Rubbia, as a heterogeneous engineer, brought together the structural, human and financial factors necessary to ensure a successful project outcome.

Both of the theoretical frameworks above have their respective advantages and disadvantages. Elkins and Keller’s (2003) R&D leader concept utilises many of the theoretical concepts considered in Section 2.3.4 such as the concept of classifying both the leader and the context. This makes it feasible to use the R&D leader as a conceptual framework in a scientific context. However, R&D is a relatively small aspect of a megascience project so I am concerned that there is a mismatch between my target population and this potential conceptual framework. The mismatch is that the R&D leader concept is an approach for investigating leadership in that specific field, but a megascience project involves a much wider variety of activities, which could affect the characteristics of leaders. While the R&D leader concept could be translated to suit scientific knowledge production, the aim of many megascience projects is to construct the new apparatus before the production of knowledge can take place. This means there is a divergence between the type of work conducted in R&D and megascience projects. The heterogeneous engineer concept can be more readily implemented in the context of megascience projects and has already been used by Krige (2001) in a similar context to my research. Based on this reasoning, I chose to adopt the heterogeneous engineer as the conceptual framework for this thesis.

During my fieldwork I hypothesised a heterogeneous engineer would be a single individual who took charge of the megascience project for its entirety from conception to the final stages. Interviewees might also have been expected to describe such a heterogeneous engineer as controlling almost all decisions over the project such as finance, timetabling, and detailed technical choices. This may even lead to the individual being described as extremely authoritarian and difficult to work with because of their insistence on taking control.

It became apparent to me during the fieldwork that the heterogeneous engineer concept was of limited value for this thesis, despite this research initially offering the possibility of using the concept to develop broader leadership theory. When I started this research, I was interested in exploiting the observation by Krige (2001) that Carlo Rubbia was a heterogeneous engineer for his involvement in a previous CERN experiment. Rubbia also worked at Fermilab for a time and was heavily involved in the LHC at its early stages, which offered a possibility that I could identify an equivalent heterogeneous engineer for both the Tevatron and the LHC. However, the interviewees usually identified Rubbia as a unique individual within science rather than a generalised example of a leader within science. I discuss this in more detail in Sections 5.4.1 and 6.1.

2.8 - Summary

In this chapter, I considered the existing knowledge within the bodies of leadership and project management literature. Sections 2.2 and 2.3 evaluated the relevant leadership literature. Two paradigms have dominated the leadership literature. The evolutionary paradigm focuses on the development of gifted individuals with various theories about how development occurs. The style paradigm, by contrast, sidesteps leadership development to focus on leadership behaviours. The literature identified five primary leadership styles. Section 2.4 considered the relevant literature from the project management domain with a particular focus on large and technologically uncertain projects. The existing literature identified that large projects have certain specific characteristics, namely the use of subcontractors, virtual teams and a high level of importance to the organisation while technologically uncertain projects may require a greater degree of flexibility (Mersino, 2007; Flyvbjerg, 2014). Generally, large projects possess a low level of technological uncertainty as they are frequently civil infrastructure such as bridges (Shenhar and Dvir, 1996).

Megascience projects are a subcategory of large projects that incorporate novel additional characteristics, in particular their significant level of technological uncertainty, a relative rarity in the large project literature. I concluded this section by restating the three research questions that this thesis aims to answer. In Section 2.5, I briefly summarised two other bodies of literature that were useful during my intellectual journey but were not appropriate to use as a primary body of literature for a thesis analysing megascience project leadership. After identifying a gap in existing knowledge, in Section 2.6 I stated three research questions to address this gap. This chapter also introduced the conceptual framework in Section 2.7, which is based on the concept of the heterogeneous engineer. Although I deemed it appropriate for this research as it requires a megascience project leader to possess a wide range of skills not just related to scientific knowledge, after consideration during the fieldwork I concluded in Section 2.7.3 that it was inappropriate for this research (Krige, 2001). I examine this issue in greater detail in Section 6.1

3 – Methodology

This chapter explains the reasons underpinning the research strategy and methods for this thesis. A range of other methods was also addressed to provide a better understanding of the reasons that I chose to conduct this research using a combination of archival research and case study methodologies. To reiterate, the research questions that this thesis aims to answer are:

1. What are the characteristics of those who lead megascience projects?
2. Where were their leadership skills developed?
3. How were their leadership skills developed?

This chapter comprises six sections. Section 3.1 addresses the overall research strategy, examining the potential strategies and justifying the selection of case study research strategy for this research. Section 3.2 considers the specifics of research design, in particular the inclusion criteria for qualification as a megascience project. Sections 3.3 and 3.4 describe the research methods selected for this thesis, namely archival research and an interview programme, respectively. In these sections, I consider how I tailored these methods to my research. In Section 3.5, I examine the potential analytical strategies for analysing my data to produce reliable results. For the purposes of this thesis, I utilised a thematic analytical process. Finally, Section 3.6 provides a summary of the chapter.

3.1 - Research strategy

The research strategy represents the framework that guides the direction taken to implement and achieve the overall research objectives. This section addresses the strategies which I considered to investigate leadership in megascience projects. Following careful consideration of the research questions and objectives, I identified two potential research strategies. These were ethnography and case studies. I consider that the two research strategies described below are the most suitable for this research. Both ethnography and case studies acknowledge the uniqueness of context; each laboratory will have differing histories that creates a narrative lens through which individuals view project decisions. The primary difference between these two potential research strategies is the unit of analysis. Ethnography observes the entire community as a unit and then in the analytical phase this unit is deconstructed with the individual strata examined for further meaning (Gold, 1997). Whereas case studies are comparatively more flexible - this allows a researcher to apply the methodology in a wide variety of topics. The choice is between a strategy with a well-defined but potentially inappropriate focus, and an adaptable strategy that can be utilised in a wider variety of topics. After carefully examining these potential benefits and costs, I judged that case study methodology was the most suitable research strategy for this thesis. In this section, I compare these two potential strategies and provide a justification for my decision to select case studies for this thesis.

3.1.1 - Case studies

Stake (2005) justified a case study by analogy with a sick child. If a child has an undefined sickness, he or she will exhibit both qualitative and quantitative symptoms. The doctor will tailor his inquiry to understand this particular case without seeking to generalise beyond it, because there is inherent value in a single unusual case. This is a justification for using case study methodology in many cases (Yin, 1994). Within the literature, there are also case studies of single laboratories (Irvine and Martin, 1984; Martin and Irvine, 1984a; Martin and Irvine, 1984b; Krige, 2001).

The consideration of multiple projects provides the basis for stronger conclusions as a distinction can be made between the discoveries unique to a single megascience project and those common to all or most megascience projects (Yin, 1994). This wider search for evidence would help to provide a more reliable basis for theory development (Stake, 2005). As I discussed in Section 2.4.4, previous research into large projects has attempted to build theory using only a single project (Arain, 2012; Olaniran *et al.*, 2015). This introduced many of methodological risks observed by Yin (1994) and Stake (2005). Therefore, I chose to consider two projects to mitigate these risks and to provide a wider basis for my findings. Although case study strategy lacks a formally acknowledged unit of analysis, it does offer a looser framework that provides the researcher with the flexibility to adapt case studies to suit a wider range of research topics (Yin, 1994).

3.1.2 - Ethnography

Ethnography is a fieldwork technique enabling researchers to gather reliable data through the development and maintenance of close contact with the community under study (Gold, 1997). It is popular in anthropology, where many communities considered primitive in the Victorian era were analysed (Gold, 1997). It is considered good research practice to spend a substantial amount of time with the subjects; Hannerz (2003) notably claimed that two years is an adequate period to observe seasonal traditions and adaptations. This has been implemented in the case of the scientific community by

Traweek (2009) and Zabusky (2011), who examined particle physicists and space scientists respectively. However, ethnography has some potential weaknesses, as its proper use requires an extended period of fieldwork, which can be incompatible with a timely delivery of results. This time restriction creates difficulties for becoming embedded in project groups and developing the necessary interpersonal contacts and tacit knowledge to become a member of the community. There is also an expected difficulty in obtaining the necessary permission to be embedded in the selected project groups. By selecting a single project for analysis, one might gain a great deal of knowledge about a single project, but the generalisability of any conclusions would be limited. Equally, should more than one project be selected and analysed with an ethnographic strategy, using the 'adequate' times referred to by Hannerz (2003), a period of four years would be spent conducting fieldwork. This is an unacceptable timeline for a PhD thesis.

A final comment relates to the lifetime of a megascience project, which can be twenty years or more (Smith, 2007; Hoddeson *et al.*, 2008). Unfortunately, due to the nature of megascience projects, there are relatively few ongoing projects at any single time. Finding two concurrent projects and spending several years with a team may not be technically feasible and, given these long project lifespans, would affect observations across the entire project lifetime.

While some work has made use of ethnographic techniques in scientific laboratories, these have tended to examine an entire laboratory or a single research group within the laboratory (Traweek, 2009; Zabusky, 2011). However, this thesis investigates a subset of the laboratory community, namely those in leadership roles, rather than the entire community. An ethnographic strategy has a well-defined focus; but this focus is unfortunately incompatible with my research questions (Douglas, 1979; Brown, 1993).

3.2 - Research design

The previous section examined the broad overall strategy that will be used for the research, namely case study methodology. This section considers the detailed methods used to implement the overall research strategy. I chose to use a combination of archival research and an interview programme. This necessitated taking into account the accessibility to archival material for the selected megascience projects and interviewees.

3.2.1 - Explaining the criteria for the selected choice of megascience projects

The nature of megascience projects results in a very small pool of potential candidates for investigation. There comes a point when a megascience project could cease being scientific and become an infrastructure project. Consider the nuclear reactor: originally it was an applied scientific experiment undertaken in Chicago, USA to see if atomic fission reactions could be controlled (Wood, 2007). This is referred to as Chicago Pile One (CP-1) (Wood, 2007). It later led to small-scale applied research into its power generation potential in the United States and Soviet Union (Wood, 2007). From this research came new innovations such as the nuclear-powered ship (Cowan, 1990). Over time, these experiments grew in scale until a small-scale reactor in the Soviet Union was attached to the civilian power grid as a technical challenge, albeit tangential to the core experimental task (Kruglov, 2002). Nuclear power became a recognised part of the energy mix much later on, when the first large-scale nuclear power station opened in the UK (Williams, 1980).

While it is straightforward to recognise the extreme points of the American pile reactor and the British power station as experiment and infrastructure respectively, the Soviet reactor is somewhere between the two. This makes categorisation more challenging. This proved an issue of some concern during the early part of this research, as it could be possible to select projects that the research community would not deem to be megascience projects. I chose to avoid this issue entirely by only considering basic science research projects, as any applied science projects could be in this 'grey area' concerned with applications rather than science itself. I broadly identified three categories defined below, these categories proved very useful when determining the megascience projects to investigate.

3.2.1.1 - Basic science experiments

Basic science experiments exist solely to create new knowledge. Any innovations with societal benefits are purely incidental and arise from the need to solve technical challenges encountered in the project. External actors may then adopt these solutions to benefit society. As an example of how these tools developed to solve internal issues can be spun off, the foundations of the World Wide Web emerged as an information management solution for CERN experiments and accelerators (Berners-Lee, 1989). Although these early developments began in the late 1980s, it took several years for the tool to be developed and released, firstly to the academic community and then later to commercial interests and consumers. Similarly, other protocols evolved to form the modern tool that we know today as the World Wide Web (Berners-Lee and Caillau, 1993; Hughes, 2002).[19]

3.2.1.2 - Applied science experiments

Applied science experiments occupy the 'grey area' outlined above in Section 3.2.1. Applied science experiments for the purposes of this thesis are defined as any experiment where there is a mixture of basic experiments and applied research with the specific intention of benefitting society, even if this is not core to the experimental programme. Examples of such projects include the National Ignition Facility in Livermore, CA. This facility is investigating nuclear fusion using extremely high-powered lasers, one possible method for a future fusion-based electricity reactor (George, 2004). The definition of applied science used for this thesis is stricter than the literature generally adopts, to minimise the previous concern from Section 3.2.1 that I might select a project that is more similar to infrastructure than to megascience (Brooks *et al.*, 1967).

3.2.1.3 - Pure infrastructure

The concept of pure infrastructure projects includes all other projects within the field of science and engineering in which the primary project objectives are non-scientific in nature. Infrastructure projects are less concerned with the scientific novelty than they are with engineering aspects. They could be considered as large engineering projects. There is a body of literature examined in Section 2.4 which investigates individual large projects. Examples of such projects in the scientific field include the first nuclear power plant in Calder Hall, Britain and DEMO, a planned successor to the ITER thermonuclear reactor (Cowan, 1990).

3.2.2 - Criteria for selection of megascience projects

The size of these projects and the association of science with national pride often makes government a substantial stakeholder in a megascience project (Floricel and Miller, 2001; Hughes, 2002; Flyvbjerg *et al.*, 2003; Smith, 2007). This introduces the risk for scientific researchers that governments will exploit their position to influence the direction of a research programme, possibly toward research with military applications. This could have

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[19] As an example of these newer protocols, the original incarnation of the World Wide Web did not have a secure access protocol (i.e. HTTPS (Hyper Text Transfer Protocol Secure) for browsers and SecureFTP (File Transfer Protocol) for file access). These protocols enabled secure credit card transactions, among other things.

made it difficult for me to access the data and project materials. I therefore chose a scientific laboratory in which military involvement is limited. Generally, there are two different scientific fields managing projects at the appropriate scale that would qualify as megascience projects - space science and particle physics. Of these two fields, the military has a more substantial role in space science than particle physics due to its more easily applied nature. Therefore, I chose particle physics projects for investigation.

An additional consideration governing which projects might be suitable for investigation concerned the *lingua franca* of the laboratory. I happen to be a native English speaker and a reasonably competent speaker of French. Given that this research will make use of archival techniques, the project selection process should consider the dominant language of the laboratory to ensure that the archival material can be understood. In North America[20] and Australasia, this will not present a problem, as English is the dominant language among the local scientific communities, although the particle physics community has yet to build a sufficiently large facility in Australasia to qualify as megascience. I still had concerns that a laboratory elsewhere may have an official language that was unfamiliar to me. Fortunately for me, in Europe, many laboratories use two languages in parallel, principally English and French. This is notably the case at CERN (Hermann *et al.*, 1987a; Hermann *et al.*, 1987b; Krige, 1997; Lederman and Teresi, 2006). Therefore, although European laboratories may seem to present a language issue on first appearance, this is not the case in practice.

A final consideration is that of culture, which can be a substantial factor governing how an organisation functions (Robbins and Judge, 2010). Culture is considered “a system of shared meaning held by members that distinguishes the organisation” (Schein, 1985; Robbins and Judge, 2010). Culture will often act as a stabilising force, creating a relatively homogeneous workforce, which influences which leadership styles are more suitable than others (Trice and Beyer, 1991; Testa, 2009; Grey, 2012). While Western societies tend to place a substantial emphasis on individual effort to elevate the group, eastern societies generally seem to be more collectivist (Robbins and Judge, 2010). This introduces culture as a variable for an appropriate leadership style, so it might be better to focus on Western megascience projects to avoid this issue. Megascience projects tend

[20] While there is a significant French-speaking scientific community in Canada, the majority of the scientific facilities are located in English-speaking areas.

to be concentrated in Western countries to date, although there are now initiatives to create multi-national particle physics laboratories elsewhere in the world (Einfeld *et al.*, 2004).

Using the above criteria coupled with an examination of megascience projects led to the identification of a list of candidate megascience projects for this thesis. They are:

- Hadron-Elektron-Ring-Anlage (HERA) at DESY. This was a German particle accelerator investigating electron-proton collisions. As I am a European Union passport holder, obtaining visas would not have been an issue. There is, however, the risk that any archival material will be in German and hence inaccessible without the use of a translator, among other difficulties; it is debatable how much value could be derived from the archives.
- The Joint European Torus (JET) at Culham. This is a European fusion experiment based in the United Kingdom designed to test the feasibility of fusion as a practical energy source for the future. JET conducts experimental research to determine the feasibility of nuclear fusion as a power source. This is similar to the Obninsk Nuclear Power Station in the former Soviet Union from Section 3.2.1, which could put JET into the ‘grey area’ described above; some researchers may consider it not experimental but rather infrastructural in nature[21]. As JET is based in Oxfordshire, it offers an advantage of convenience, being closely located to my home institution, but they appear to maintain no physical archives.
- The Large Hadron Collider (LHC) at CERN. This is a particle accelerator in the French-Swiss border region commissioned in 2008[22]. It has an ongoing experimental program and at the time of writing has recently been upgraded to increase its collision energies to its original design capacity (Smith, 2007). It is currently the most powerful particle accelerator in the world and in its brief period of operation has already discovered a particle with characteristics matching the theoretical predictions of the Higgs boson, the quantum of the Higgs field. This

[21]Unlike the Obninsk nuclear power station, which was connected to the power grid as a technical challenge, JET is not and will not be attached to the power grid. The next phase in the development of nuclear fusion for power is the construction of ITER, a large-scale experiment to produce fusion power, followed by DEMO which will be a reactor attached to the power grid (EFDA, 2014). It would not be appropriate to describe JET as civil infrastructure rather than an experiment because it will not become part of the energy mix.

[22] This project also has interesting additional factors such as its place on the cutting edge of scientific research and its international nature.

particle is theoretically responsible for governing which particles possess mass (Perkins, 2000; Smith, 2007).

- The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. This is a US-based particle accelerator specialising in relativistic heavy ion collisions (Riordan *et al.*, 2015).
- The Tevatron at Fermi National Accelerator Laboratory (Fermilab). This was a US-based particle accelerator at Fermilab in the United States. It commenced operation in 1983 and closed in 2011 (Hoddeson *et al.*, 2008; Grim, 2011). Until 2010, it was the most powerful accelerator in the world, accelerating two beams in a circle in opposite directions multiple times before colliding them. Scientists working with the Tevatron discovered many new particles before its closure due to budget cuts (Krige, 2001; Oddone, 2011).

When I considered the sites above, it seemed appropriate to select one project each from Europe and North America for comparison of leadership styles in differing 'host' cultures (Testa, 2009; Hofstede *et al.*, 2010). More importantly, keeping the investigations to a similar field of science avoids the risk of introducing the type of science as a variable. From the list above, there were two projects in a similar field. These are the Tevatron and the LHC. Some literature identifies a rivalry between the two laboratories that constructed these machines (Wilson, 1970; Irvine and Martin, 1984; Martin and Irvine, 1984a; Martin and Irvine, 1984b; Hoddeson *et al.*, 2008). These two cases therefore provided a rich base to investigate the types of leadership that each project had exhibited in pursuit of their similar 'missions'.

3.3 - Archival research

Archival research, one of the methods chosen for this research, involves the interpretation of pre-existing data, eliminating the need to go into the field because data collection is already complete (Jackson, 2010). One of the primary justifications of archival research is to develop a sense of how policy evolved or to understand the context (Geiger, 2011). However, data reliability is an issue when collection is a third party activity (Geiger *et al.*, 2010). Researchers can never guarantee data reliability because it may have been biased during collection or purged afterwards (Geiger *et al.*, 2010; Jackson, 2010). If such a bias exists, it can be extremely challenging to remove it, which influenced my decision to mitigate this risk by using archival research in combination with an interview programme (Geiger *et al.*, 2010; Jackson, 2010).

Archival research, however, is potentially a very useful source of data as it offers information about how leadership evolved and changed to suit the needs of the organisation or project (Geiger, 2011). Archives offer easy data access at low cost that can be used with another method to validate claims. However, relying on it as a sole source of data can be problematic. To mitigate this risk, and given that the two projects under investigation were relatively recent events, it seemed reasonable to combine archival research with an interview programme to help to triangulate the claims made in one area with another (McNabb, 2004). A combination of archival research and a well-designed interview program offers the opportunity for direct contact with leaders and team members to obtain first-hand information and clarification, when necessary, on leadership characteristics.

Gaining access to the Fermilab archives proved to be straightforward. I contacted the Fermilab Archivist in May 2013 and within a few days, I received her approval to access the Fermilab archives. Although I was not able to begin my fieldwork until the beginning of 2014, I used the intervening period to construct an interview schedule. I spent January and February of 2014 at Fermilab on a US J1 visa, passing the relevant radiation safety tests required by all employees and visiting researchers.

The process to gain access to the CERN archives proved much more challenging. Although some historical accounts exist on the origins and evolution of CERN, these were commissioned projects and the procedures for gaining archival access have since been tightened (Hermann *et al.*, 1987a; Hermann *et al.*, 1987b; Krige, 1997). The new procedure is to restrict all access to documents for 30 years. Access can be granted in certain exceptional circumstances but this requires written permission from the CERN Director-General. I submitted a formal application for access to the archives in August 2013 and finally received exceptional approval from the Director-General a year later in August 2014. The reason for the extended timetable was primarily because the CERN legal department wished to consider my application. I conducted my fieldwork at CERN in January and February 2015 although there were a few occasions where key individuals had left the laboratory. In those unusual cases, I undertook a separate trip to meet with them.

3.4 - Interview programme

Interviewers seek to understand the central themes under investigation according to those being interviewed (Valenzuela and Shrivastava, 2002). Through the interview process, a good researcher should be able to interpret both explicitly stated facts and the implicit meaning of the interviewee speech and body language (Valenzuela and Shrivastava, 2002). The direct contact with the interviewees produces theoretically 'better' data (Valenzuela and Shrivastava, 2002). However, if the interviewer is not well trained, the interview can easily veer off-topic as the interviewee defines the most relevant themes (Valenzuela and Shrivastava, 2002). This offers both opportunities and risks as new unforeseen insights can emerge so an interviewer must be capable of distinguishing a potential insight from 'noise' (Scott *et al.*, 1990; Valenzuela and Shrivastava, 2002).

As this research aims to gather information on the characteristics of leaders, an interview programme is the more appropriate as it entails identifying and interviewing key individuals. In the case of Tevatron, where the project is complete, a combination of archival material and snowball sampling was used to identify the interviewees. A snowball sample relies on the researcher asking a single interviewee if there is anyone else who might also be as helpful as a potential interviewee (Atkinson and Flint, 2001; Vogt and Johnson, 2011). This allowed me to tap into existing social networks and, although it can take some time to find an initial respondent, the identification process should speed up after the initial breakthrough (Thompson, 1997; Atkinson and Flint, 2001). Many of those involved with the Tevatron still live in the Chicago area so it was feasible for me to interview them. In the case of the LHC, many of the key individuals were also easily accessible on-site, although a few interviews required a specific trip to their new home institution.

3.4.1 - Interview format

Generally, the face-to-face interviews lasted between one or two hours with some exceptions; one notable interview lasted approximately three and a half hours. I undertook a brief pilot study to trial my interview questionnaire – this involved meeting with a few members of the University of Sussex Physics department. Questions were added, removed, refined, and reworded to make them appropriate for the interview programme, which was conducted primarily at Fermilab (Batavia, Illinois, USA) and CERN (Geneva, Switzerland)

The initial stage of arranging interviews varied between the two sites. When conducting fieldwork at Fermilab, I was provided with a number of contacts who were involved with the Tevatron and I made an initial informal approach via the Archivist. This involved simply asking candidates whether they were willing to have their contact details passed on to a leadership researcher. The Archivist was involved primarily to ensure that potential interviewees would respond quickly and positively. I also felt that it was courteous to provide potential interviewees with a discreet opportunity to decline without feeling rude. An internal employee making an informal move would normally receive a quick positive response rather than an external researcher asking about a meeting in six months. If they replied positively, the Archivist would pass on their information to me. This approach allowed the use of internal social networks to build up a pool of candidates. The second phase was a formal request by me via email for an interview. The request included a brief introduction to the research topic and the dates I was available to conduct an interview. This was followed by an arrangement to agree a mutually convenient date. Upon confirmation of the agreed date, I provided the interviewee with electronic copy of the questionnaire and their data protection rights. By providing these documents at an early stage, the candidate would have time to consider their answers and be in a position to give informed consent. Copies of these documents are available in Appendix 2.

I used a different method at CERN owing to different administrative procedures and approached interview candidates directly at the first stage via email, asking if they wished to participate in the research, i.e. an approach similar to the second phase outlined above. If the interview candidate was willing to be interviewed, then we began to discuss the specifics, which included providing them with electronic copies of the interview documentation. This bypassed the risk of accidental censorship but it took longer to gather a pool of suitable interview candidates.

The original expectation was that interviewees would be extremely busy, so I initially only asked interviewees for a one-hour appointment. However, many of the interviewees were very interested in the topic and we spent a great deal of time discussing the key issues. The format evolved according to interviewee comfort and feedback. The starting format was a brief discussion to introduce the interviewee to the topic before proceeding to the questionnaire. Over the course of the interview programme, this format changed to a far longer initial discussion lasting about one hour before the questionnaire. This necessitated requesting longer appointments when I first approached subsequent new interview candidates. Using the experience of the pilot study, I decided that interviewees who were aware that they were being recorded were less likely to be open about their experiences than those who were unaware. Although I experimented with using audio recording, I had noticed during these informal pilot discussions that an interviewee's eyes kept looking toward the recording device with an accompanying hesitation. As an alternative, I kept paper notes, despite the risk of precision loss, to create a more relaxed atmosphere. These interviewees were more forthcoming in their responses and views. I developed a personal shorthand to keep up with the interviewees comments and rarely ran into any difficulties 'keeping up' with interviewee comments.

3.5 - Methods of analysis

Following the data gathering, it was necessary to devise appropriate analytical methods to process the raw data to produce reliable results. There were three potential methods – thematic, textual and discourse analysis. In this section, these analytical tools will be briefly introduced and discussed to justify the most appropriate method for this research– thematic analysis.

3.5.1 - Thematic analysis

Thematic analysis, which was the analytical process that I used for this research, is a way of examining broad trends within a dataset (Miles and Huberman, 1994; Pope *et al.*, 2007). It begins with the observation of a common factor or theme in seemingly random information, then develops further into a description, and an interpretation of the meaning of the theme (Pope *et al.*, 2007). The distinction between theme and 'noise' is left to the researcher (Pope *et al.*, 2007). Combatting the risk of unintentional bias and distinguishing themes in seemingly random information is termed pattern recognition. Corbin and Strauss (1990) stated that the ideal researcher would possess a sufficiently open mind to observe patterns without preconception. Relevant understanding is crucial; this knowledge allows the researcher to see what is important, give it meaning and conceptualise the observations. Miles and Huberman (1984) discussed the importance of clustering themes together to move toward higher levels of abstraction. To sense such themes, researchers must be open to all information and it helps if they understand the fundamentals of the relevant field. The second stage is being able to use codes reliably and consistently. These codes are developed to interpret the information and themes in the context of a theory or conceptual framework.

However, thematic analysis does not delve into minor details of the data, instead examining broad trends and these are then used as the basis for theory development. This would be useful in the research as Section 2.6 identified a gap with regard to leadership in megascience projects in the literature on leadership. Leadership is a broad concept, and it is undesirable to identify the characteristics of leaders based on minor details. I therefore chose to approach the data with an open mind and to use the principles of grounded theory when analysing my data by basing my work on themes rather than fine detail. This required me to go through the coding process, which I describe in Section 3.5.4. As this thesis aims to identify the characteristics of leaders in megascience projects, thematic analysis was adopted to reveal these traits.

3.5.1.1 - Considerations relating to the use of grounded theory

I found it useful to consider some of the principles of grounded theory during this research. Grounded theory is utilised by researchers when there is little understanding about a phenomenon under investigation and predetermined hypotheses are unwise (Miles and Huberman, 1994). According to Glaser and Strauss (1967), who developed grounded theory, in such a situation it is better to develop open codes after data collection where codes can be created as necessary (Tracy, 2012). These small data points can then be combined into larger concepts, which in turn can then be grouped into categories as the basis for theory (Corbin and Strauss, 1990). However, a grounded theory approach dictates that that no literature can be examined before data collection, whereas I conducted an extensive literature review before conducting my research and then concluded that my findings could be mapped onto some existing theories (Corbin and Strauss, 1990; Corbin and Strauss, 1994; Liyanage and Boisot, 2011). Nonetheless, I sought to incorporate the principle of keeping an open mind during my data analysis.

3.5.2 - Textual analysis

Textual analysis comprises identifying the purpose of text based on the communicative elements structure, and how the author of the text pursued their line of argument (Helder, 2011). It can also be used on rare occasions to analyse internal context on the basis of certain display techniques such as font, although given that certain organisations may use established identity guidelines, this seems to be of questionable use (Helder, 2011). One example of display techniques illuminating such an internal context is the use of italics adding emphasis to what the author deems an important consideration (Helder, 2011).

The literature indicates that almost anything can be considered as a 'text' (McKee, 2003; Helder, 2011).

Texts are seen as the product of social events, mediated by the social structure of the organisation, its social practices, and its relationship with external stakeholders. These documents are therefore useful socially constructed artefacts that can indicate context within certain boundaries of language (McKee, 2003; Fairclough *et al.*, 2011). These texts indicate what the organisation considered possible, likely, and impossible at the time of writing. What the literature calls 'the social structure and practices' seems very similar to what other bodies of literature call 'organisational culture', which also governs what is structurally possible and what is subject to change (McKee, 2003). Textual analysis aims to provide both an understanding of the evolution of a single text and to identify how a text influenced other texts. In this way, the evolution of an argument as presented in the text can be charted. The textual analysis can look at the broad structure and the evolution of arguments as well as detailed analysis of individual words.

In my research, most of the archival material at the laboratories was comprised of project documentation such as project meeting minutes and other reports. These followed set guidelines and pre-determined agendas. These meeting minutes examined the agenda on project progress rather than the topic of this thesis, namely leadership. However, there were many opportunities to identify key challenges to use as prompts in the interviews. Examining these texts from a pure textual analysis perspective could overlook important insights into leadership because I intended to use the archival research to identify important issues that could be discussed in the interviews. However, the justification for applying textual analysis to the interview data is less clear. As I consider in below in Section 3.5.3.1, spoken language data is less organised than textual data as conversations will move between issues and backtrack to previously discussed issues (Dexter, 2006). Therefore, written interview notes produced during the interviews are generally not suitable for textual analysis as they are less structured than documents that can be produced from recorded interviews. Textual analysis examines written documents in detail, sometimes even down to the typeset. However, the research methodology chosen to combine interview and archival research creates concerns that textual analysis might artificially generate insights from 'off the cuff' remarks. This may be an inappropriate basis for theory development.

3.5.3 - Discourse analysis

Discourse analysis examines language in its everyday use, including non-textual material such as speech, but in contrast to textual analysis, widens the pool to include non-verbal behaviour and the relationship between the two. There are two types of discourse - transactional discourse for pure information exchange, and interactional discourse describing social relations between parties (Brown, 1983). For the purposes of this thesis, most archival material was transactional, although the subject of leadership is interactional in nature. These different types of discourse will be delivered in spoken language, which can then be preserved for future analysis as spoken text.

Transactional discourse is used to express content and transmit information (Brown, 1983; McCarthy, 1991). This style of discourse summarises events with the intended purpose of changing the situation (Brown, 1983). This is the standard method of communication used in workplace meetings and the resulting minutes

Interactional discourse expresses social relations within groups; this encompasses most communications where there is no real aim of information transfer (Brown, 1983; Brown and Levinson, 1987; McCarthy, 1991). It does, however, lead to beneficial outcomes primarily in establishing common ground and good interpersonal relations (Brown and Levinson, 1987; McCarthy, 1991).

For this research, interactional discourse was useful to understand the nature of how future leaders were identified and developed during the megascience projects. As leadership is generally not a topic that laboratories are likely to communicate in their archives, understanding the interactional discourse within the laboratories helped me to understand the perception of certain leaders. Although I did not use discourse analysis as my primary method of data analysis, I did seek to use its principles in real-time during the interviews to understand how the interviewees regarded specific leaders.

3.5.3.1 - Spoken language and texts

Spoken language is verbal communication between two or more people in which the speaker is free to make use of differing tones, facial expressions, and gestures to give further meaning to their words (Brown, 1983). In written text, the author can look over what they have already written, consider exactly what they mean in their writing and even look things up if necessary before transmission (Brown, 1983). By contrast, spoken language will move from one topic to another based on interactions and what the speaker deems important, and then move back to topics previously discussed as new facts are remembered (Brown, 1983). This can make a purely spoken language discourse appear disorganised to an external observer (Brown, 1983). The speaker *should* know his audience and can modify what they say to make it more acceptable to the listener. These messages are rarely analysed in real-time but are turned into a spoken text for analysis.

Spoken texts records are more useful than a spoken language from a research perspective as these artefacts preserve a conversation for future analysis (Brown, 1983). One tool frequently used is a tape recording to preserve the 'text' of the spoken language. This may also preserve ambient sounds, which can provide context, or cues that lead to topic changes. Generally, researchers use tape recordings to make an annotated transcript. A great deal of context can be lost from these events and writing things phonetically has been recommended (Brown, 1983). Spoken language is often less structured than written communication; expressions may be refined as the conversation proceeds. It is frequently useful to re-arrange the transcript to unify topics to account for these clarifications. These refinements can provide important contextual clues as to the nature of a phenomenon (Brown, 1983).

I decided not to record the interviews. This was on the basis of experience from the pilot study indicating that interviewees who are recorded are less likely to be candid about their experiences compared to when written notes are made (Yin, 1994). While certain minor fine details may have been lost, useful data was identified from these written notes. Equally, discourse analysis can lead one to delve too deeply into the minutiae of the conversation rather than focussing on the topics covered. But it proved a useful starting point for analysing interview notes prior to pooling the data from the archives and interviews.

3.5.4 - Data analysis method

In this section, I outline the steps I took to analyse the data obtained from the archival and interview research conducted at Fermilab and CERN. I converted the handwritten notes into text-based computer files immediately after each interview. This also provided me with an opportunity to document any non-verbal gestures given by the interviewees. I thanked the interviewees for their time via email and notified them that, if they had any additional comments they wished to make or clarify, they should feel free to do so. Several interviewees chose to avail themselves of this option by making minor adjustments to quotes or providing me with additional comments or documents to help me understand their key points. This process gave me a familiarity with the context to interviewee statements, and provided me with an understanding of internal power dynamics that I could discuss with subsequent interviewees. Even at this point, I began to consider how I might go about coding the information and what codes were likely to appear.

During the analytical portion of this research, I printed out these typed copies of my interview scripts and unified the relevant topics by placing them in physical arrays at an open coding stage. Although I tested what might be considered appropriate software for the analysis of my data, I found that it was unable to deliver adequate performance and therefore resorted to manual analysis. For example, I unified all interviewee comments about democratic leadership into a ‘democratic leadership’ array and all training-related comments in a ‘training’ array. When some statement elements could be considered to belong in two arrays, I duplicated the statement and inserted it into both of them. At this early stage, I kept the data from the Tevatron and LHC fieldwork separate. I then examined each statement element within a single array and wrote it down in my notebook to gain a greater familiarity with the concepts articulated by the interviewees.

Over the course of three months, I used a highlighter to indicate important themes that emerged within a single array and theorised how these themes might relate to leadership in megascience projects in line with the principles of Yin (1994). This process also helped me to identify when certain common themes emerged. I applied this technique firstly to introductory questions that I thought were unlikely to contribute significant insights into leadership such as what motivated an interviewee to pursue science as a career. I then applied this process to all of these data, keeping notes on how my leadership theories were developing. The theory that required the most significant time investment was the theory that the laboratories sought to tailor the selection of their senior leader to suit the needs of the project at that point in time. Once I had composed a theory explaining each array, such as the needs of the project at a given point in time and how the senior leader met these needs, I integrated these single theories to form a broader understanding of how leadership manifested itself in each megascience project. The final stage in the process was to compare the theories that had emerged from each separate case study to determine what factors were common to both case studies and to examine whether these theories could be explained using existing knowledge.

3.6 - Summary

In this chapter, I discussed the methodology which was to combine an appropriate research strategy and design. Two potential research strategies were discussed - ethnography and case studies. While ethnography has a well-established methodology and a clear unit of analysis, my research focussed on a subset of the scientific community. Additionally, the aim of this thesis is to identify the characteristics and development of leaders and not to study their rise to power, which seems to be a feature of many ethnographic leadership studies (Douglas, 1979; Brown, 1993). Case studies, by contrast, offer a greater degree of flexibility to define the unit of analysis rather than consider an entire population. For these reasons, I selected case studies as the research strategy.

The research design to implement this strategy required consideration. I devised selection criteria to ensure a suitable pool of candidate megascience projects while examining what combination of methods might best be used to analyse my data. In Section 3.2, I reduced the potential laboratory options to the final two sites. These were the Tevatron at Fermilab in Batavia, Illinois in the United States, and the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland, at both of which I undertook the archival and interview research.

The purpose of the archival research was to determine internal project management procedures, examine whether there is or had been any consideration of leadership, and identify discussion prompts to be used in the interviews. A combination of archival research and interviews offered the opportunity for direct contact with these leaders to obtain first-hand information on leadership characteristics and to triangulate claims.

Three analytical methods were identified as potentially useful for this research. These were textual, discourse, and thematic analysis. After considering the relationship between research method and analytical technique, I felt that a textual or discourse method of analysis, although appropriate for examining the fine details of a phenomenon, is not appropriate for examining a broad phenomenon such as leadership. Thematic analysis examines broader trends characterised in leadership styles rather than fine details, making it an appropriate choice for the investigation of a topic on leadership

4 – Case Study 1 – The Tevatron at Fermilab

This case study draws on the archival and interview research that I conducted and on relevant secondary literature to analyse and discuss the leadership findings in the case of the Tevatron at Fermi National Accelerator Laboratory.[23] This case study seeks to answer the research questions, which, to reiterate are:

1. What are the characteristics of those who lead megascience projects?
2. Where were their leadership skills developed?
3. How were their leadership skills developed?

Section 4.1 comprises a background to Fermilab and the Tevatron. Section 4.2 explores the findings related to the first research question, which sought to identify the characteristics of leaders, in the specific case of the Tevatron. Section 4.3 delivers the findings in relation to the second and third research questions to understand the nature of leadership development at Fermilab. During the fieldwork, an unexpected but important leadership-related observation emerged, that different laboratory directors were selected to meet the phase-specific needs of the Tevatron, and Section 4.4 explores this topic. Finally, Section 4.5 summarises the findings from this chapter.

As part of the archival research, many documents were analysed to identify important events during the Tevatron programme that could be used to identify key players with the aim of informing additional questions for the interview programme. Although these documents did not directly discuss or address the concept of leadership, they provided useful discussion points and indicated the evolution of the projects.

During the fieldwork, I interviewed 15 individuals representing a broad cross-section of the Fermilab community. This included several project leaders, key individuals involved in the departmental structure, and scientists working on problem-focussed tasks such as machine design and construction.[24] Four interviewees from the Large Hadron Collider fieldwork also worked at Fermilab during this time and offered comparative comments on their experiences at Fermilab and CERN. It was not possible to interview the two individuals who served as directors over this time on health grounds.

[23] More commonly known as Fermilab.
[24] A copy of the consent form and interview script is available in Appendix 2

4.1 - Fermilab: background

Fermilab was built in response to claims from the scientific community that some particle physics laboratories were inhibiting collaborations with external scientists; Fermilab as a 'neutral' location did not restrict access on the basis of institutional affiliation (Lederman, 1963; Hoddeson and Kolb, 2003). Interviewee F7 described some of the underlying motivations behind the foundation of Fermilab:

> *"In '58 both [the University of California] Berkeley and Brookhaven*[25] *were rivals and wouldn't let outsiders in to experiment. MURA*[26] *in Wisconsin wanted an unclassified machine so that any experimenters all over the world could come and experiment without the fear of government secrecy. MURA built a strong focussing synchrotron as a sign that they wanted to make a collider... Berkeley and Brookhaven fought it out [for the funding to build such a machine]. The result was that UC [University of California, Berkeley] won and could build the 300GeV machine but they only managed 200GeV. Wilson designed his own machine and toured the country showing it could be done cheaply. Bob [Wilson] wanted a big site with lots of room for expansion. (Source: F7)*

The two key particle physics laboratories in the 1950s, the University of California, Berkeley, and Brookhaven, fought for the right to construct a 300GeV accelerator. The Lawrence Berkeley Laboratory 'won' the competition but later only submitted design reports for a 200GeV accelerator at a significantly higher cost than originally submitted (Hoddeson *et al.*, 2008). In order to pull the community back together after the competition and open up these new facilities to outsiders, the Universities Research Association (URA) was formed to construct the 'Berkeley' 200GeV design and select an alternative site. Robert ('Bob') Wilson, then Professor of physics at Cornell University,

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[25] Berkeley refers to the University of California at Berkeley and its associated laboratory the 'Radiation Laboratory' (Now referred to as Lawrence Berkeley Laboratory). Some interviewees also referred to it as UC, I have kept their original wording. Brookhaven refers to Brookhaven National Laboratory in Brookhaven, New York State. During this period, Brookhaven was associated with nine prominent US east coast universities.

[26] MURA (Midwestern Universities Research Association) was the name given to a consortium of fifteen universities in the American Midwest proposing to build laboratory in the 1950s and 1960s. Unfortunately, MURA was unable to meet its financial or technical goals and was subsequently shut down in 1963. Many members of MURA later went on to work at Fermilab during its early years.

designed an alternative accelerator costing one third as much as the Berkeley design, opening up the possibility to achieve or even exceed the original 300GeV target (Hoddeson *et al.*, 2008). The site competition selected a site near Chicago, leaving the original Lawrence Berkeley Laboratory constructors remote from the new location. During the nomination process for the new laboratory's director, Wilson's proposed frugal design distinguished him from other candidates and heavily influenced his subsequent selection as the first director of Fermilab (Wilson, 1970; Anon, 1978; Hoddeson, 1987; Glanz, 2000; Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008). Although relatively little archival material relating to the foundation of Fermilab is available, because the 'History and Archives Project' did not begin until Fermilab's tenth anniversary, there are *post-facto* accounts of Fermilab's foundation written by key players. These accounts are referred to as the 'golden books'. In the Fermilab archives, the then-URA President described Wilson wanting a specific type of challenge:

> *"At a Trustees meeting on January 15, the position of director was offered to Robert Rathbun Wilson, whose new Cornell synchrotron had just been completed one year ahead of schedule. Although Bob Wilson indicated almost immediately that he was interested and would probably accept, he withheld his formal acceptance until the Atomic Energy Commission assured him that it would satisfy conditions, which would enable the project to move rapidly and to be scientifically exciting. These agreements later proved to be of immense value to the project, but they did delay Bob's formal acceptance of the post…" (Source: The Fermilab Golden Book – The Early History of URA and Fermilab. Viewpoint of a URA President)*

Wilson's founding vision for the laboratory combined the symbolism of the nineteenth century 'American frontier' and of the scientific frontier (Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008). The quote below from the Fermilab archives demonstrates Wilson's vision in which the 'beauty of science' could be investigated in beautiful surroundings:

> *"Those early meditations of mine were often a kind of a fantasy in which I envisaged the Laboratory as a utopian place where physicists coming from all parts of the country -- and from all countries -- would*

> *be doing their creative thing in an ambiance of well-functioning and yet beautiful instruments, structures, and surroundings that would reflect the aesthetic magnificence of their discoveries and theories. All this to be done in a scientific climate of mutual respect and responsibility; it would be a place where, according to the Chinese ideal, "All would be happy to do what they had to do, and would have to do what they were happy to do."*
>
> *My fantasy of a utopian laboratory clearly required a setting of environmental beauty, of architectural grandeur, of cultural splendor, but therein lay the rub: money." (Source: The Fermilab Golden Book – Starting Fermilab)*

The origin of this vision can be ascertained from the many articles written about Wilson's early life with a key influence being his childhood in Wyoming, a view with which Wilson himself agreed (Wilson, 1970; Glanz, 2000; Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008). One novel in particular inspired him to pursue science, namely *Arrowsmith* by Sinclair Lewis (Wilson, 1970). In this novel, the titular character advances from humble beginnings in a small American Midwestern town to the very top of the scientific profession, with key themes being the independence and frontier-like nature of research. Wilson's vision for the laboratory likewise incorporated these themes and symbols (Hoddeson *et al.*, 2008). This included a frugal attitude to science that Wilson developed during his time at the Radiation Laboratory at the University of California, Berkeley under the supervision of Ernest Lawrence (Heilbron *et al.*, 1981a; Seidel, 1983). As I noted in Section 1.1, Lawrence influenced many scientists trained in the 1920s and 1930s (Heilbron *et al.*, 1981b; Seidel, 1983). Hoddeson *et al.* (2008) obtained the following quote from Wilson that exemplifies this frugal attitude:

> *"…that something that works right away is over-designed and consequently will have taken too long to build and will have cost too much." (Source: Hoddeson et al. (2008))*

This quote could also be viewed as a criticism of the European particle physics laboratory CERN, which during this time operated what several authors such as Martin and Irvine (1985) and Hoddeson (1997) described as a "gold-plated" style of physics. This alternative style of science emphasised reliability and perfection rather than the Fermilab approach of a quick launch followed by rapid iterations. These two differing approaches to particle physics quickly led to a rivalry that Leon Lederman described as:

> *"…collaborative competition" (Source: Fermilab Annual Report 1983)*

The following quote from Interviewee F6 demonstrates that his long-term colleagues were also aware of Wilson's frugality:

> *"I've spent 20 years working with Bob [Wilson] even before FNAL [Fermi National Accelerator Laboratory, the formal name for Fermilab]. Bob [Wilson] was driven, forceful – build it quick and cheap, then fix it." (Source: F6)*

In keeping with these themes of frontier and frugality, many of the pre-existing barns and houses were turned into laboratory facilities, with the most vivid symbol of the American frontier being an on-site herd of bison (Hoddeson *et al.*, 2008). Finally, Wilson's frugal science policy, which prized pioneering technology over reliability, affected certain choices during the construction of the original Fermilab accelerator (Krige, 1997). This did lead to many technical issues, as Krige (1997) and Interviewee F7 described:

> *"The main ring was built for 500GeV but never really made it; it operated around 350, once they hit 450" (Source: F7)*

The idea of the Tevatron arose early in the life of Fermilab as part of Wilson's vision for Fermilab exploring new scientific frontiers but it was many years before technical advancements made it feasible, as these quotes from Interviewees F6 and F7 demonstrate:

> *"When Bob [Wilson] arrived, very soon he wanted to build a superconducting ring accelerator. Focussed on building it and the lab." (Source: F6)*

And:

> *"Bob [Wilson] always had a plan for a bigger machine than the Main Ring… when superconductivity appeared on the horizon; Bob [Wilson] noticed its potential and started quietly moving things." (Source: F7)*

There were two directors over the lifetime of the Tevatron. Wilson served as director during the R&D phase of the Tevatron (Hoddeson *et al.*, 2008). He later resigned in protest over allegedly inadequate funding of the Tevatron's transition from R&D to construction, leading to the selection of Leon Lederman as the new director (Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008). Wilson's frugal attitude also included the opinion that new technology automatically justified investment, which conflicted with the US government desire for a return on investments (Seaborg and Seaborg, 2001; Hoddeson *et al.*, 2008). Lederman managed to secure sufficient funding to enable this transition and oversaw the Tevatron programme through to completion in 1985 (Hoddeson *et al.*, 2008).[27] The observation that the selection of directors of a large laboratory could be tailored to suit the phase-specific needs of the project is a significant finding of this thesis and is further addressed in specific relation to Fermilab in Section 4.4 and in more general terms in the discussion in Section 6.4. A team of associate directors working in the directorate supports the director. These associate directors undertake important support activities that ensure the smooth running of the laboratory such as budgets, visa requests, and maintaining relations with other laboratories.

I chose to distinguish between senior leaders, middle management, and task-focussed leaders on the three level model used by Mumford *et al.* (2007) that I discussed in Section 2.3.2, a model which divides an organisation into senior, mid, and junior levels based on the differing skill requirements. I chose to retain the senior level title but to rename the 'mid' and 'junior' levels as 'middle management' and 'problem-focussed leaders'. For this specific case study, I consider the Fermilab directors as 'senior leaders' with associate directors in the directorate, project managers, and departmental heads deemed to be 'middle management'. All leaders below this level are primarily working hands-on with the technology and are thus 'problem-focussed leaders' (see Figure 1 for a diagram illustrating the three level model and Fermilab's relationship with URA who act on behalf of the US Department of Energy).

[27] Additional information regarding the historic context of both the Tevatron and LHC is given in Appendix 1.

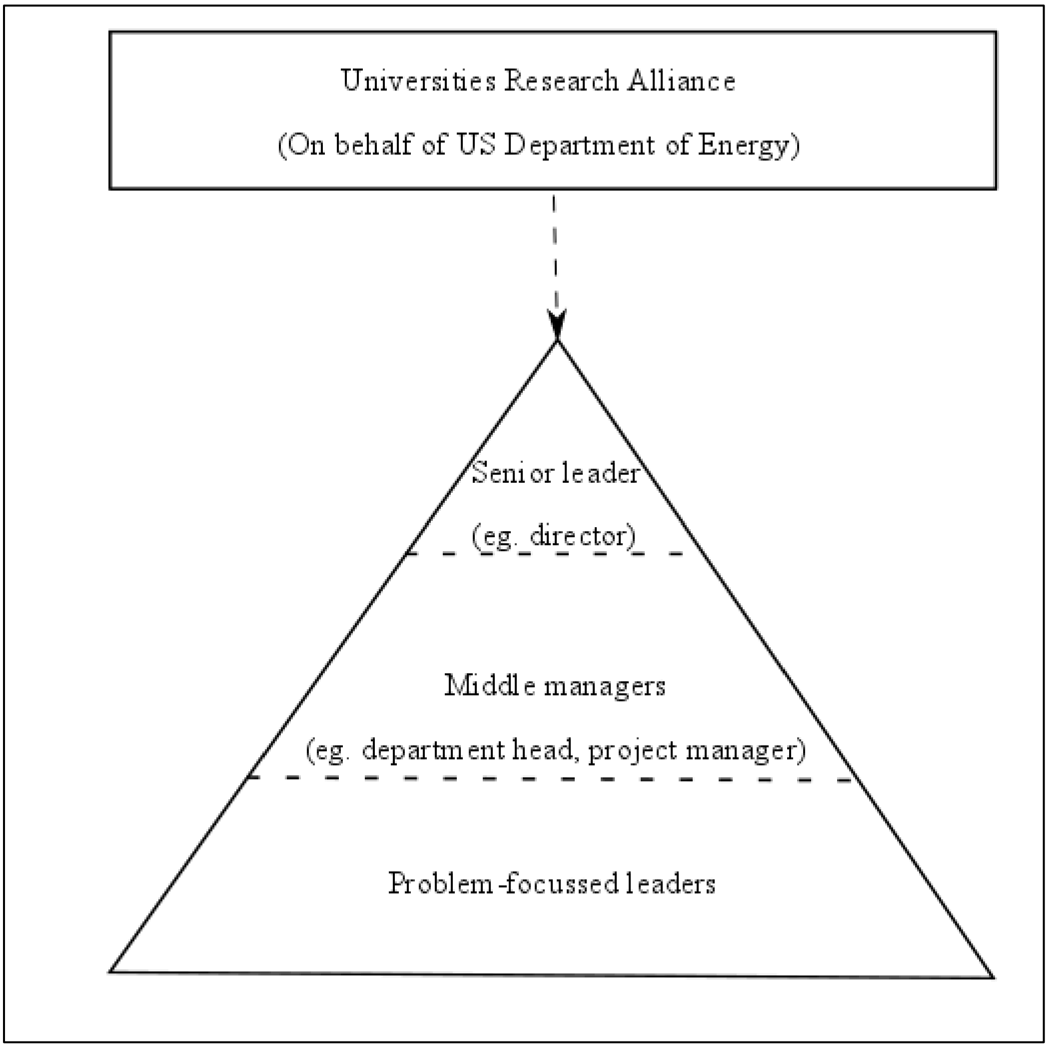

Figure 1: Diagram showing the organisational structure of Fermilab in the context of the three level model for analysing leadership

Fermilab has had an occasionally turbulent relationship with the US Department of Energy, as described in Appendix 1, often claiming that politicians exploited science for political purposes. This may be for historical reasons stemming, which I consider in Section 4.4 (Hoddeson *et al.*, 2008). Another possible reason for this dislike could be the founding principles of the laboratory, where Wilson embraced the symbolism and rhetoric of the American frontier with the accompanying “antipathy to control” documented by Hoddeson *et al.* (2008).

4.1.1 - Tevatron: background

The Tevatron was a particle synchrotron that achieved proton-antiproton collisions at a world record energy of 1TeV. Its development required the first application of new technologies in particle physics, principally helium-cooled superconducting magnets (Hoddeson, 1987). This makes the Tevatron arguably a class ‘C’ or class ‘D’ project based on the Shenhar and Dvir (1996) classification scheme discussed in Section 2.4.3. Essentially a class 'C' or class 'D' project is one with a high or very high level of technological uncertainty, respectively. The original programme budget estimate was US$300 million with an approximate final construction cost of US$450 million or US$1billion in 2012 prices (Webre, 1988). A 1983 Fermilab internal costings report conducted two years before completion of the programme puts the budget at approximately US$410 million, although the Tevatron I project experienced significant delays and cost overruns after this date (Jordan and Livdahl, 1984). Later estimates including subsequent infrastructure upgrades increase the total cost to an estimated US$4 billion in 2012 prices (Womersley, 2012). This meets the budgetary criterion for a megascience project outlined in Section 2.4.1 of a minimum budget of US$1 billion.

The construction of the Tevatron was not a single project but rather a programme composed of three projects:

1. *The Energy Doubler/Saver*. This project involved the construction of a superconducting ring of magnets. It was described by two names over its lifetime, originally the Energy Doubler and later the Energy Saver. The project leader for the Energy Doubler/Saver was Helen Edwards, who had extensive experience in the design and construction of accelerators, and who played a very active role during the early life of the accelerator (Hoddeson *et al.*, 2008; McDaniel and Silverman, 2009). The quote below briefly summarises the Energy Doubler/Saver lifecycle:

    > *"The world's first superconducting accelerator went into operation after six years of R&D and four years of combined R&D and construction.*
    >
    > *Two objectives were served by the construction of the Energy Saver. As the name suggests, the power consumed by a superconducting accelerator with its associated refrigeration is far less than that which a conventional accelerator uses. Moreover, the superconducting magnets can reach much stronger magnetic fields, permitting acceleration to 1000GeV in the same tunnel as the original 400-GeV facility [The Main Ring]." (Source: The Dedication of the Energy Saver April 28, 1984 – Program)*

Despite certain issues,[28] Edwards still managed to get the project completed on time, although not on budget (Webre, 1988). The total project cost according to the archives was US$206million (Jordan and Livdahl, 1984).

2. *Tevatron I/Anti-Proton Source.* This involved constructing the infrastructure and carrying out various upgrades to allow proton-antiproton collisions. Originally this project began as an R&D project to determine the best method for creating an antiproton beam under the title 'Anti-Proton Source'. The program for the dedication ceremony for Tevatron I best summarises what it was and how it related to the rest of the Fermilab accelerator complex:

> *"This is designed to provide an intense source of antiprotons and to arrange head-on collisions of protons and antiprotons at a total energy of 2000-billion [eV] in the Tevatron… It required the construction of 700 magnets ranging from small, precision trim magnets to 50-ton monsters built to Swiss-watch tolerances. It involves very precise electrodes to sense the position of particles, and electrodes to correct these motions." (Source: The Dedication of the Proton-Antiproton Collider (Tevatron I) October 11, 1985 – Program)*

The project was likely originally classified as a Shenhar and Dvir (1996) class 'D' project with an R&D phase to determine the most appropriate mechanism to sustain an anti-proton beam. During this R&D phase, a scientist called Don Young ran the effort and there was a change in leadership and branding after its subsequent incorporation into the Tevatron programme. During this process the project was re-named Tevatron I and the new project leader was John Peoples, Jr. Peoples had an interesting educational background, originally trained in engineering before spending time working at the Martin Aircraft Corporation, the industry where formal project management was first developed (Cleland and Ireland, 2006). Peoples subsequently became the Fermilab director in 1989 and sought to maximise the performance of the Tevatron while also placing Fermilab in a position to weather the crisis in American

[28] Although there were few technical issues during the construction, there was an extended commissioning process. According to information obtained during the archival research, the laboratory considered this an unavoidable consequence of operating at the limits of technology.

particle physics following the collapse of the SSC in 1993 (Hoddeson *et al.*, 2008; Riordan *et al.*, 2015). The Tevatron I project had a more troubled lifetime compared to the other projects in the Tevatron programme: in particular, a key physical mechanism failed to operate as expected. This was resolved when Lederman intervened and selected an alternative but proven method, which substantially increased costs and resulted in schedule slippage as a key project technology went back to first principles (Möhl *et al.*, 1980). This method was described in the program for the dedication of the Proton-Antiproton collider:

> *"The Fermilab design, based on CERN's experience and on several years of R&D at Fermilab, was radically modified as a result of new ideas and new technological possibilities." (Source: The Dedication of the Proton-Antiproton Collider (Tevatron I) October 11, 1985 – Program)*

This is an interesting point given the director's personal intervention into the issue, and it is addressed further in Section 4.2.8. Based on documentation from late 1985, the project cost was US$134.5million.

3. *Tevatron II*. This comprised the infrastructure to enable fixed-target collisions. The project leader for Tevatron II was Tom Kirk, a scientist with significant fixed-target experimental experience (Anon, 1982). The project progressed smoothly with only a marginal cost overrun, apparently because most of the incorporated technologies were relatively mature (Webre, 1988). It was also significantly smaller in budget at US$70million (Jordan and Livdahl, 1984).

4.2 - What are the characteristics of those who led the Tevatron?

This section is concerned with seeking to answer the first research question in the specific case of the Tevatron. All of the interviewees had served in leadership positions in some way. Therefore, they were in a good position to comment on leadership characteristics during the Tevatron programme, with both their personal experiences and observations of leadership styles. In many cases the interviewees observed commonalities in successful leaders and when identifying future leaders. In these cases, the interviewees also discussed the relationship between leadership and management to help establish if management is a characteristic of leaders in megascience projects; this discussion included whether it was realistic for a Fermilab leader to be both a leader and a manager.

4.2.1 - Technical competence

All interviewees identified technical competence as the single most important characteristic of leaders in the Tevatron. Interviewee F2, for example, stressed how it is:

> *"… most important to gain the respect of people with your technical ability. Authority needs ability." (Source: F2)*

This perception of the need for technical competence existed for all levels of the organisation. I have quoted three interviewees on the importance of technical competence. The first is from Interviewee F2, who described it in relation to a traditional corporation:

> *"Technical skills are very important, [while] in business conglomerates such as GE, you can't understand the technical side because you do so many things, so the business side has to be enough." (Source: F2)*

This illustrates the perception that many large organisations are involved in a wide variety of fields, thus preventing the leader from being technically competent across all fields. However, scientific laboratories and megascience projects in particular are more focussed in scope, which makes technical competence more important. Interviewee F7 described technical competence as one third of the important triumvirate of leadership:

> *"Leaders need vision, intuition in the absence of quantification, and technical skills." (Source: F7)*

Interviewee F8 shared a particularly memorable experience, one that reveals how technical competence can provide a foundation for respect in a politically sensitive situation. During his first project at Fermilab, he was deciding whether to stay on or return to his home institution:

> *"…what convinced me to stay was over a question raised over reconfiguring the system; many said it was politically sensitive and not technically possible. My supervisor said 'Sure you can try but you've got until 6am' [i.e. the next day]. So, I worked all night and at 6AM the supervisor arrived with the Russian contingent and I demo'ed the new system over the course of two hours. It was better and most importantly, my supervisor never took the credit for it - it was all me." (Source: F8)*

This is a good example of technical competence leading to future career success; as Interviewee F8 later went on to occupy senior positions in several Tevatron experiments.

4.2.2 - Management ability

In the literature considered in Section 2.2.1, leaders can assume a more transactional style of leadership towards the end stages of a project (Bass, 1990; Conger and Kanungo, 1994; Kirkpatrick and Locke, 1996). This shift to more transactional behaviour can be necessary to complete the project that gives the leader a base of credibility for delivering projects (Tracey and Hinkin, 1998). Such transactional behaviour is often associated with management rather than leadership. However, it is documented in the literature that Fermilab staff generally believe that too much management is bad for science (Wilson, 1970; Wilson, 1977; Anon, 1978; Glanz, 2000; Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008). Most of the discussion with interviewees related to their personal experiences of leading teams and perceptions of the relationship between leadership and management. While the interviewees regarded leadership positively, there was greater suspicion concerning management. All but one of the interviewees did make a distinction between leadership and management in line with the literature, with the sole dissenting voice seeing leadership and management as identical.

Leadership was considered to have a quality, best defined by Interviewee F8 as:

> *"…a creative element. It's about changing the status quo, having a vision, and creating tasks and ideas… [whereas management is about] well-defined outcomes within resource and time constraints and reacting to crises by staying on-task" (Source: F8)*

According to Interviewee F11:

> *"Management really means being details-oriented and keeping track of things but leaders bring people together." (Source: F11)*

Interviewee F9 suggested a symbiotic relationship between leadership and management:

> *"A manager is an implementer of another's vision. Not a leader. They're one level down from the leader. You can be a good leader with poor management skills but the manager has to be details-oriented to get things done so being inspirational isn't important." (Source: F9)*

The interviewees therefore perceived the Fermilab leadership-management relationship as broadly similar to that in most organisations rather than as something unique to science. What emerged during the discussions with two interviewees in particular was that many individuals with management skills became associate directors within the directorate where they completed the necessary background work to achieve the leader's vision. In this case, the associate directors filled in skill gaps and played an important role in implementing the director's vision:

> *"Leaders use much broader statements and allow the deputies to do the dirty work." (Source: F5)*

And:

> *"Bob Wilson had charisma, was risk-taking and flexible. But the associate directors did the dirty work of managing business admin and keeping things under control." (Source: F2)*

It appears that generally, leadership may manifest itself anywhere within Fermilab but individuals with management skills work in the Directorate to keep the laboratory running. These associate directors often had a broad range of competencies. The associate directors who I interviewed suggested they had planned to follow a different academic pathway, only selecting physics at a relatively late stage. The alternative pathways cited most frequently were liberal arts and business studies. These interests later re-emerged in their future responsibilities in the form of appointments that could exploit both their scientific and their other competencies. One notable example was an individual with business interests who became head of the technology transfer department, where technical competence worked well with an appreciation of commercial realities.

4.2.3 - Leadership styles

To uncover additional characteristics of these leaders, I queried interviewees on their view on the five leadership categories discussed in Section 2.2, and the applicability of each leadership style within Fermilab, which arguably could also be relevant generally to megascience projects. To remind the reader, these styles are transformational, transactional, authoritarian, laissez-faire, and democratic. During the discussions, many interviewees spoke of their experiences interacting across the laboratory and categorised these interactions and specific individuals in terms of these leadership styles. From these discussions, I discovered additional characteristics of leaders within megascience projects. However, some of these characteristics exist at some levels of the organisation while others are deemed redundant elsewhere.

4.2.4 - Transformational leadership

The literature in Section 2.2.1 presented the key components of transformational leadership. These are the creation and implementation of a vision while using charisma to achieve revolutionary change (Bass, 1990). All interviewees felt that transformational leadership was highly appropriate in megascience projects. Every interviewee described anecdotes about leaders that correlate with descriptions of transformational leadership.

4.2.4.1 - The communication, inspiration, and implementation of a vision

Section 2.2.1.1 indicated that a charismatic communication style is generally reflected in the expression of high expectations of followers and confidence in their abilities to meet those expectations to achieve a vision (Shamir *et al.*, 1993). The vision is therefore a highly seductive tool for gaining and motivating a team. Charisma is, however, a situated phenomenon that is highly dependent on how the leader is perceived by the team, with charisma being defined by its observers (Conger and Kanungo, 1994). Each interviewee described at least one anecdote about leaders that revealed his/her perception of charisma. These interactions with leaders displayed not just the vision each leader had of the future, but also the need to work hard while still maintaining a light tone and even a sense of humour. Two individuals emerged repeatedly as having particularly distinctive communication styles. These individuals were Wilson and Lederman.

Interviewee F5 provides his perception of Wilson's charisma:

> *"I threw my hat in the ring when NAL [National Accelerator Laboratory – the original name for Fermilab] first came up. Bob [Wilson] interviewed me with the statement 'What can you do for me?'" (Source: F5)*

The majority of anecdotes related to Lederman. Several interviewees spoke of the atmosphere he created, the excitement they felt about coming to work each day, and the fond memories they had of the parties held during Wilson and Lederman's tenures. Interviewee F5 described:

> *"People here would move mountains if necessary. The Main Ring [the accelerator before the Tevatron] was a tunnel full of mud, but they set the last magnet and they wanted to have their reward. And what they wanted was a pizza party in the tunnel… oh, the parties, Leon [Lederman] once wore a suit of armour and rode a horse into Wilson Hall [the main administrative building] at one." (Source: F5)*

I found photographic evidence confirming some of these party claims pinned to office doors around the laboratory. These parties evidently have become part of the laboratory folklore. Another anecdote, which was supplied by Interviewee F8, occurred while Lederman was being shown around the laboratory, after the announcement of his appointment but before his tenure formally began:

> *"We first met on my birthday, Leon [Lederman] was being given this tour by some guys from URA [Universities Research Association – the consortium that runs Fermilab] – and we were celebrating my birthday with some champagne. Leon [Lederman] came over looking slightly stern and asked 'Why are we celebrating your birthday?' to which I said 'Well, I'm not dead yet'. Well Leon [Lederman] just beamed and said 'That's a great response, have another glass of champagne'." (Source: F8)*

Five interviewees found it impossible to understand how a leader could progress without a vision. They also wondered about the role of leadership without a vision. Interviewee F11 said:

> *"…being a leader means having a vision, communicating that vision to motivate others to perform hard work… [to] unite with the vision." (Source: F11)*

Nine interviewees described two individuals as particularly embodying transformational leadership; these were the Fermilab directors - Robert Wilson and Leon Lederman. A majority of the interviewees (see below) who attempted to categorise Wilson's or Lederman's leadership used a combination of styles to describe them. As I noted in

Section 2.3.5, Turner and Müller (2005) suggested that a combination of leadership styles is possible. From the two sections below it is apparent that charisma and a vision is an essential characteristic of senior leaders at Fermilab. Elsewhere within the laboratory, charisma and a vision are not considered as essential as middle managers in particular are principally tasked with implementing this vision.

4.2.4.2 - Robert Wilson as a transformational leader

Seven interviewees described Robert ‘Bob’ Wilson as a charismatic transformational leader not just for his work on the Tevatron but also, as the laboratory’s first director, for building Fermilab the institution. Interviewee F2 described Wilson’s behaviour as director:

> *“Bob [Wilson] was a good leader. He created Fermilab and subsequently created many of the teams by interaction. He designed Wilson Hall [the main administrative building] to maximise interactions and he definitely practiced ‘management by walking around’. Visible. Charismatic.” (Source: F2)*

This Interviewee F2 quote demonstrates the observation that Wilson bringing Fermilab into existence represented something of a revolution which was accompanied with several other unusual developments. Notable among these was his personal involvement in the aesthetic design of the laboratory, personally designing the main administrative building to encourage employee interactions. However, taking such a keen personal interest could be interpreted as authoritarian leadership as well as transformational, as Interviewee F1 indicated:

> *“Wilson was a transformational leader with authoritarian characteristics. He had vision and charisma and was definitely highly motivated but drove people out.” (Source: F1)*

During the fieldwork, I attended an ‘all-hands’ meeting conducted by the recently selected new director at Fermilab, in which he laid out his own vision for the future of the laboratory. This ‘all-hands’ meeting was very similar to a ‘town hall’ style meeting as all members of the laboratory workforce had the opportunity to hear the director and ask him questions (Bryan, 2010). Essentially the new director’s vision involved the modernisation of the laboratory facilities and consolidation of two areas of the laboratory, one called the 'village' and the other which comprised most the scientific apparatus and office space. During discussions with colleagues, several voiced disquiet that this might destroy Wilson's original vision discussed in Section 4.1. One specific concern was that a road might be constructed through the restored prairie as had apparently been attempted on a previous occasion. These informal conversations demonstrate the power and pervasiveness of Wilson's original Fermilab vision even decades after his tenure ended. Wilson is very much still a presence at Fermilab, to the extent that he was buried on-site, something requiring special dispensation from the US Department of Energy (Hoddeson *et al.*, 2008).

4.2.4.3 - Leon Lederman as a transformational leader

Leon Lederman was the second director of Fermilab, with his tenure running from 1979 to 1989 (Hoddeson *et al.*, 2008). Five interviewees directly characterised him as transformational, although as with Wilson they most often used a combinations of leadership styles to describe him. Six other interviewees spoke about Lederman's leadership behaviour and these descriptions corresponded most closely with the transformational leadership style. Although Lederman's vision for Fermilab continued some aspects of the preceding Wilson vision such as the Tevatron and frontier atmosphere, he also introduced his own vision. This change was reflected in the varying combinations of leadership styles used to describe Lederman, with no interviewees describing him as authoritarian and many seeing him as more democratic, as this quote from Interviewee F2 indicates:

> *"Leon [Lederman] was a mix of democratic and transformational leadership." (Source: F2)*

Interviewee F9 described Lederman's ability to communicate to a wide variety of audiences, with a particular focus on speaking to children to excite them about science. This is an important factor when one considers his desire to introduce science to wider audiences as discussed above:

> *"Leon [Lederman] was charismatic, amazing communicator. Could formulate and communicate. Make decisions as well. He had vision and he was unusual for all these things. He was also a very funny guy and could talk to kids, to scientists and to politicians, and adjust his speech to suit his audience." (Source: F9)*

This quote from Interviewee F8 demonstrates a similar observation while also illustrating what he believed was Lederman's charisma:

> *From 1979 until today, he was a person of well-defined love and passion for his work. Science education was his passion. [His] Honesty was a motivation to me personally. I once was in difficulties with a project manager I had a problem with and as a last resort, I went to Leon [Lederman] and shared my issues, and he said to me: 'What do you want to do?' I looked at him and all I could say was 'I just want to do science'. Leon [Lederman] said 'If you want to do physics, then I'm for you'." (Source: F8)*

4.2.5 - Transactional leadership

As discussed in Section 2.2.2, transactional leaders work within existing cultures to achieve change and only intervene in tasks when performance deviates from expectations (Bass and Avolio, 1993). Transactional leaders induce subordinates to comply with their wishes by using the prospect of reward or punishment to achieve the specified goals (Bass and Avolio, 1993). About half of the interviewees felt that there was a place for transactional leadership in megascience projects in a specific situation, namely during a crisis. However, the three interviewees who supported the idea of transactional leadership spoke strongly against punishing scientists for mistakes, Interviewee F2 in particular said:

> *"Reward ...yes... but not punish. Scientists are not drones, they're intelligent people. Having said that, you can definitely be transactional at the end stages when things are more certain." (Source: F2)*

Interviewee F5 shared Interviewee F2's view of the role of reward and punishment. Only two interviewees, one being Interviewee F8, characterised the threat of punishment as being useful and then only during certain situations such as when there was a desperate need to bring matters back under control:

> *"...during a crisis – 'If you do this bad thing, I will do this bad thing back so you learn'." (Source: F8)*

This quote suggests that, while transactional leadership has its place in megascience projects, it should only be used temporarily during crises or near the project endpoint. This explains why transactional leadership was only observed at Fermilab at these project end stages when the main technical challenges are resolved and the project manager can focus almost solely on completing the project on-time and on-budget.

4.2.6 - Laissez-faire leadership

Laissez-faire leadership is categorised in the literature as allowing the group to set goals while the leader pursues a policy of non-intervention (Bass, 1990; Woods, 2004). All but one of the interviewees had rather negative views on laissez-faire leadership, with the exception being Interviewee F5, a human resources specialist. Their comments were broadly similar, describing laissez-faire leadership as not being leadership but rather a way of abdicating responsibility. This is exemplified by Interviewee F3 describing how laissez-faire leadership:

> *"…implies laziness. You need to be building solutions while keeping support. You have to be a cohesive unit and build a consensus" (Source: F3)*

And Interviewee F9 simply stating that it:

> *"…doesn't work." (Source: F9)*

Determining the reason that laissez-faire leadership was deemed inappropriate therefore stimulated an invigorating part of the discussion with interviewees. Interviewee F8 articulated the most specific reason why laissez-faire leadership was inappropriate in science:

> *"Laissez-faire isn't really leadership. During a crisis you can't just ignore it – you have to address it. Authoritarian leaders could create a crisis intentionally; a laissez-faire leader could create one by inaction." (Source: F8)*

However, upon further discussion, Interviewees F3 and F9, who provided the strong reactions above, moderated their statements somewhat. In my opinion, this is because their initial reaction was subsequently tempered by discussing the issue that led to second thoughts. Interviewee F3's moderating statements for example, suggest that there was some utility in laissez-faire leadership, should the highly unusual scenario occur in which the leader was not technically competent. This could occur in an entirely new technological field:

> *"It can be useful with high tech as you can't know everything. Others say it isn't leadership at all. Still others say you get the resources and let people get on with it. But it depends on the team and the task." (Source: F3)*

Interviewee F9 later described how:

> *"Laissez-faire can be important too. If the situation isn't a problem, then leave them alone to get the work done. Micro-managing is destructive." (Source: F9)*

This illustrates that, although most interviewees did not see much merit to laissez-faire leadership, once their initial reaction had subsided there was some limited acknowledgement of its utility, even if in very specific circumstances. These circumstances were when the leader was not technically competent in the specific field or where the team had already found an optimal way to accomplish tasks. The interviewees argued that when such a situation arises, the leader should focus on resource acquisition and allow the team to get the work done. This is because micro-management of teams was felt to be destructive and incompatible with Fermilab's culture of "antipathy to control" described by Hoddeson *et al.* (2008). This adds further weight to the opinions expressed in Sections 4.2.6 and 4.3.1 that a Fermilab leader should allow the team to develop and find their own ways to accomplish tasks. Witness Interviewee F5's response, whose background is in human resources:

> *"...I think I was laissez-faire because I wasn't technically competent when setting up the medical office [Where Fermilab employees could receive on-site treatment and advice] but I still needed to give guidelines and parameters such as workplace disclosure when the pain could affect work or was being affected by their work." (Source: F5)*

Two interviewees described the directors as laissez-faire in some situations, with Interviewee F11 describing Wilson's attitude toward accelerator construction:

> *"Bob [Wilson] was very laissez-faire when it came to some things – build the machines and they will come." (Source: F11)*

Interviewee F1 recognised that his own opinion of Lederman probably categorised him as having some laissez-faire tendencies:

"Leon Lederman was democratic and laissez faire, allowed lots of leeway, and F1 felt they could go on vacation when he was there. Had different effects, with the troops he could be a leader and with others a friend." (Source: F1)

This also indicates Lederman's charisma in which he had a relatively close inner circle with whom he would go travelling. However, with the wider Fermilab community he was a leader and commanded a position of respect.

From this discussion, I identify that leaders at Fermilab act to liberate their teams. While it is extremely rare for an individual to lead a Fermilab team when they are not technically competent in the technology, giving teams the freedom to determine how to accomplish tasks is a sign of respect for the team's own technical competence. Interviewee F6 articulated the risk that the rest of the organisation could include unhelpful bureaucracy that could impede team progress:

"When bureaucracy creeps in, try to shield the team from it. Maintain the balance between paperwork and real work… between ideas and moving forward, and bureaucracy which is just churn." (Source: F6)

At Fermilab, the leader acted a focal point to both represent the team externally and act as a conduit for the team when additional resources were required. Unfortunately, this included extending the frontier-like disrespect of authority to include certain aspects of the laboratory's oversight such as the Department of Energy.

There was a common attitude that leaders should acquire resources and act as a barrier to protect the team from external interference, freeing the team up to complete the task in the way they deemed appropriate. Two interviewees had a pre-existing interest in leadership and studied at least some literature before I interviewed them and provided me with of these documents. The first – Interviewee F3 – provided a document to me from the Tao Te Ching[29]:

"When the master governs, the people

are hardly aware that he even exists.

[29] The Tao Te Ching was a Chinese text that was an important influence on Taoism. It was written around the 6th Century BC.

Next best is a leader who is loved.

Next one who is feared.

The worst is one who is despised.

If you don't trust people,

you make them untrustworthy.

The master doesn't talk, he acts.

When his work is done

the people say, "Amazing: We did it, all by

ourselves!""

This illustrates the attitude held by five Fermilab interviewees and implied by the rest that the aim of leadership is to liberate the team from external interference and allow the team to pursue their own methods within reason.

The second document, provided by Interviewee F2, also illustrated this attitude. This particular document was a message send by the Duke of Wellington to the Foreign Office during the Peninsular War in 1812. In this message, the Duke presented the Foreign Office a choice between minimising waste and achieving objectives:

> *"This brings me to my present purpose, which is to request elucidation of my instructions from His Majesty's Government so that I may better understand why I am dragging an army over these barren plains. I construe that perforce it must be one of two alternative duties, as given below. I shall pursue either one with the best of my ability, but I cannot do both:*
>
> *1. To train an army of uniformed British clerks in Spain for the benefit of the accountants and copy-boys in London, or perchance.*
>
> *2. To see to it that the forces of Napoleon are driven out of Spain."*

This document illustrates well the attitude amongst those five Fermilab interviewees that leaders have a choice to decide whether to liberate their team to achieve tasks, even if there is some additional waste, or keep their own superiors happy. Other interviewees also shared this attitude as such Interviewee F9:

> *"[On being a leader] … listen, process information, cut to the chase and foster team spirit… try to get buy-in from the team. Give credit to the troops – praise in public, criticise in private. All the pieces and all the people are important. You need to create the feeling that the team thinks you're competent and care and appreciate them" (Source: F9)*

And Interviewee F8:

> *"[While discussing effectiveness] …means being able to articulate the goal of the masses and identifying a path to achieve goals... Allow deviation and convince people. Being a leader is being a focal point." (Source: F8)*

Other interviewees noted that, while it was important to promote a good atmosphere, the importance of completing tasks should not be overlooked. This was described by Interviewee F6 as follows:

> *"…show your confidence in the people but don't just turn them loose. Push them but not beyond reason." (Source: F6)*

Furthermore, about half the interviewees said a good leader should allow followers to cultivate their own ways of achieving goals. Interviewee F5 felt that what was particularly important was the:

> *"… need to have explicit goals. But also don't insist on the method; allow them to develop unique ways of accomplishing goals. Encourage them, check to see how progress is going and then congratulate or show them how to improve next time." (Source: F5)*

This shows how at Fermilab, the method of task completion is best left to the discretion of the individual researcher, in a manner similar to many other high technology organisations (Kidder, 1981; Riordan *et al.*, 2015). This was further enhanced by

Interviewee's F3 description of the widely held attitude amongst ten of the Fermilab interviewees that leadership is a partnership to both act as a team focus and develop the team:

> *"If you have a good stallion, then you let him take the reins sometimes." (Source: F3)*

What Interviewee F3 meant by this quote is that the relationship between the leader and the rest of the team is a partnership between trusted equals and the leader should sometimes trust individuals or the entire team to find their own methods of achieving goals. This is a very tight-knit relationship, one in which the leader must understand each individual's strengths and weaknesses, which may become useful for identifying future technical or leadership talent. This suggests that team or group leaders within the Tevatron practise a style of leadership bearing some similarities to other high technology organisations, but with this additional quirk. The implications of where and how potential leadership talent is developed are addressed in Section 4.3.

4.2.7 - Authoritarian leadership

Authoritarian leadership can be considered in contrast to laissez-faire leadership (discussed above in Section 4.2.6) in that, while laissez-faire leadership decentralises decision-making, authoritarian leadership centralises it with the leader (Bass, 1990). There was unity amongst interviewees that authoritarian leadership would not work in science. Yet despite the initial perception of interviewees, there is evidence that authoritarian leaders have been successful within science, both externally and internally, with both the interviewees and the literature suggesting that Wilson and even Lederman had some authoritarian moments (Hoddeson *et al.*, 2008). The gulf between perception and evidence is significant and is addressed in Section 6.2.5, which discusses and compares the relevant findings from the two case studies. Interviewee F1 commented that some leaders at Fermilab could be:

> *"...dictatorial but it was tolerated provided you [the leader] were technically competent." (Source: F1)*

In the case of Wilson, Hoddeson *et al.* (2008) note that he took a very active role in the Tevatron R&D process by dominating specific technical discussions and decisions

(Hoddeson *et al.*, 2008). Indeed, several of the technical decisions that Wilson had to be reversed at a later date, as Interviewee F7 described:

> *"… Bob [Wilson] would need people to clean up his ideas to make them work. He cut the budget for magnets and almost got into trouble for it… Cornell had to step in to fix his designs on more than one occasion. Luckily with the Tevatron, Helen Edwards [the project leader for the Energy Doubler/Saver] insisted that the machine would need correction coils… Bob [Wilson] just wanted his 1TeV." (Source: F7)*

Although there are examples of authoritarian leadership in science, the literature generally considers these exceptions (Heilbron and Seidel, 1989). Wilson's authoritarianism might be considered something of an exception, but Lederman had similar moments as well. As Appendix 1 describes, according to Hoddeson *et al*. (2008) Lederman sought to create unity around his Tevatron proposals before his tenure had formally begun and organised a "Saturday morning shootout", as Interviewee F2 described it, although most other interviewees and the literature referred to it as the "Armistice day shootout" (Hoddeson *et al.*, 2008). Several working groups analysed the potential options and presented their findings at this event. According to Hoddeson *et al. (2008)*, this was a democratic event, with internal and external experts invited to critique the proposals and with Lederman making the final decision. However, five interviewees who were at the event were unsure whether it was truly open and democratic. Interviewee F2, who received extensive business management training, found it a defining moment for Lederman guiding the democracy:

> *"Leon [Lederman] kept his own counsel and decided for himself, possibly even before the presentations had started but he needed to give the impression of democracy." (Source: F2)*

Clearly, there was an element of exploitation of the imagery of democracy to gain legitimacy for the decision. The interviewees were questioned further about this apparent disconnection between their perceived unsuitability of authoritarian leadership and well-known instances of successful authoritarian leadership both in Fermilab and elsewhere within the scientific community (Krige, 2001; Riordan *et al.*, 2015). The interviewees acknowledged this disconnect but were unable to reconcile the disparity. This led to discussion around the idea of 'guided democracy' within megascience projects. The interviewees described this as maintaining democracy at lower levels while senior individuals retained the ability to make key decisions themselves. I consider this below in Section 4.2.8 in specific relation to Fermilab and in the context of both case studies in Section 6.2.6.

4.2.8 - Democratic leadership

Democratic leaders set general strategy and allow followers to determine how to achieve the specified goals while reserving the right to intervene as necessary (Bass, 1990; Gastil, 1994; Wood, 2007). Democratic leadership was presented to the interviewees generally in contrast to laissez-faire and authoritarian leadership considered above, although I went to great lengths to avoid conflating democratic leadership with ideas of democratic political governance. All interviewees agreed that democratic leadership was useful in megascience projects. However, Interviewee F8 suggested that he agreed:

> *"… with the idea of democratic leaders because of the structure of science. I try to be one. But there's also a link with transformational leadership. Nelson Mandela was one for transforming South Africa from apartheid to democracy without a civil war." (Source: F8)*

This is interesting as most literature categorise leadership into the five discrete categories rather than using a combination of styles. This is further illustrated by Interviewee F8's categorisation of Lederman as:

> *"…a mix of democratic and transformational leadership." (Source: F8)*

Turner and Müller (2005) provided an example of the use of a combination of styles, but this was limited to varying concentrations of transformational and transactional leadership. Interviewee F8 also commented on the merit of mixing leadership styles, with two-thirds of interviewees describing leaders at Fermilab using a combination of styles. However, as suggested earlier in Section 4.2.7, five interviewees suggested that it might be useful to exploit one style of leadership while being another. Interviewee F2 described this as follows:

> *"Democratic leaders may give the impression of democracy but this may not be a reality. But it's useful to give this appearance but steer when necessary." (Source: F2)*

Interviewee F5 agreed with Interviewee F2's assessment:

> *"...democratic [leadership] worked at other times while reserving certain decisions." (Source: F5)*

This issue of 'guided democracy' within megascience projects also arose during the LHC fieldwork and it is addressed in Chapters 5 (case study on LHC) and 6 (Discussion). One memorable example of steering democracy occurred during Tevatron I, one of the projects within the Tevatron programme. As identified in Section 4.1.1, Tevatron I suffered from technical difficulties. In this case, one of the key technical methods used to prevent beam spread[30] in the anti-proton beam failed to function as planned (Hoddeson *et al.*, 2008). While detailed discussions with the interviewees about the events that took place 30 years ago were not possible since memories have faded over time, the archival material provided some additional information. It further reveals how democracy has limits and a senior leader must occasionally assert their authority to prevent one aspect of the project causing substantial cost overruns and delays. Had Lederman not intervened, a democracy might not have been able to recognise the most appropriate solution for the Tevatron programme as a whole.

During the R&D segment of the Tevatron I project, Wilson's pursuit of 'frugal science' discussed in Section 4.1.1 pervaded the laboratory. This precluded using expensive beam spread solutions such as using an alternative all-stochastic cooling method, which was discounted on cost grounds despite being demonstrably superior (Fraser, 1997).[31] As a result, the Anti-Proton Source under the leadership of Don Young pursued an electron-cooling based scheme which had the potential to be significantly cheaper than other methods (Hoddeson *et al.*, 2008). However, this research did not fulfil expectations during the three years of investigation and by 1980, the group had concluded that electron cooling was not a feasible method. During this time it appears that the R&D was managed as a technically uncertain project with greater tolerance given to increased costs and timelines (Shenhar and Dvir, 1996). Lederman reorganised the effort as his directorship began, because an antiproton beam of sufficient quality was key to achieving 1TeV

[30] The process to prevent beam spread is referred to as 'cooling' in the parlance of particle physics (Perkins, 2000).

[31] Van der Meer and Rubbia later used this all-stochastic cooling method in efforts to discover the W and Z bosons, for which they were awarded the Nobel Prize. This subsequently led to Krige's (2001) characterisation of Rubbia as a 'heterogeneous engineer'.

collisions (Hoddeson *et al.*, 2008). In this case, the effort was brought in under the Tevatron programme umbrella, rebranded it a ‘Tevatron I’, and John Peoples Jr. was appointed as the new project leader: he was described by Interviewee F6 as:

> *“…his [Lederman’s] top lieutenant.” (Source: F6)*

When the project management group first began meeting in 1980, they offered four technical options. These were:

> *(1) A precooler cooler design with all the antiprotons you could ask for*
>
> *(2) An all-stochastic antiproton cooling scheme*
>
> *(3) A boxcar stacking of antiprotons in a smaller precooler ring*
>
> *(4) Antiproton deceleration and cooling in a set of four rings.*
>
> *When asked what happens at the end of the day, Leon [Lederman] said ‘I make a decision’.” (Source: Project Management Group Meeting Minutes from November 21, 1980)*

Lederman subsequently selected an all-stochastic cooling scheme:

> *“The following decisions are irrevocably made (until someone convinces me to change them)” (Undated memo attached to Project Management Group Meeting Minutes from September 10th 1981)*

The fact that Lederman made the final decision was not regarded as authoritarian behaviour. The interviewees viewed the final decision as requiring an overview perspective of the programme and an understanding of how technologies interfaced. At this time Lederman would have known that all-stochastic cooling schemes provided a workable solution, as one was already being used for experimentation at CERN (Fraser, 1997; Krige, 2001).

After Lederman made these decisions, the archival documentation stops being concerned with *what* cooling scheme to use but becomes rather more concerned with *how* to implement the chosen scheme, as these quotes from 1982 and 1984 demonstrate:

> *"Challenges with gaining the attention of a major contractor [Name redacted for commercial reasons] over developments with sub-subcontractors but the delays can be made up following gaining their attention. The sub-subcontractor wasn't showing up for work and causing 11 days of delays thus far… Contractor will be charged for the delay" (Source: Project Management Group Meeting Minutes from September 23 1982)*

And:

> *"Small and large quadrupoles are acceptable but small dipole construction has been delayed so that production won't start until July. Seventeen weeks of total delay also including issues with the target hall and ring enclosures. Nine weeks of delays due to bad weather. Delays are seriously jeopardising the source test in the first half in 1985" (Source: Project Management Group Meeting Minutes from June 4 1984)*

Although these two quotes do indicate a project suffering from substantial delays, most of these delays are due to factors that could be experienced in any project rather than being down to fundamental technological issues. However, the quotes clearly demonstrate how democracy in a megascience projects has limits and a senior leader must occasionally guide the democracy towards what they considered the rational decision.

4.2.9 - Summary of the characteristics of leaders during the Tevatron

To summarise the answer to the first research question, there are multiple leader characteristics were exhibited during the Tevatron programme. These included technical competence, management ability, charisma, vision, respect for the team, and the ability of individuals to exploit some of the style and rhetoric of democracy while actually taking steps to control decision-making. These characteristics did vary depending on the position in the organisation occupied by the leader (See Table 4 for a full summary of the characteristics).

Characteristic	Restrictions
Technical competence	Essential for all leaders
Management ability	Useful for senior leaders but can be outsourced to middle managers
Charisma	Essential for senior leaders, useful but unnecessary elsewhere
Vision	Essential for senior leaders, redundant for others
Respect for the team	Essential for all leaders
Exploiting democracy	Useful for senior leaders to take control but retaining workforce support

Table 4: A summary of the characteristics of Tevatron programme leaders and which organisational levels the characteristics were observed

4.3 - Where and how were their leadership skills developed?

This section seeks to answer the second and third research questions in the specific case of the Tevatron, which for clarity are:

2. Where were their leadership skills developed?
3. How were their leadership skills developed?

The initiatives and programmes used for leadership development are often interrelated, so considering the two together is appropriate. Many of the interviewees spent a significant portion of their careers at Fermilab, so had personal experiences of the leadership development process. Other interviewees arrived early in the life of Fermilab and spent a significant portion of their careers there so they were involved in the evolution of the Fermilab way of developing leaders.

4.3.1 - Cultural factors affecting leadership development at Fermilab

As discussed in Section 3.2.2, culture has been cited as a key factor governing the internal performance of an organisation (Robbins and Judge, 2010). Culture acts to create a generally homogeneous workforce and influence decisions regarding the cultivation of leadership during the Tevatron programme (Trice and Beyer, 1991; Testa, 2009). There was a definite dislike of what was perceived as ‘external interference’ at Fermilab. This has been a long-standing characteristic of Fermilab, with Hoddeson *et al*. (2008) describing a cultural “aversion to control” which extends to the US government department responsible for oversight of the laboratory, the Department of Energy. Over the course of many years, a culture had developed at Fermilab in which the Department of Energy was viewed as not acting in the best interests of science or scientists, as the quotes below demonstrate:

> *“DOE [An acronym used to refer to the Department of Energy] uses an almost dictatorial way. In the old days, only the director would worry about finite resources, that was his job. Nowadays we’re all worried about it. But we are grateful for the money we get as it’s a gift to follow what interests us.” (Source: F7)*

And:

> *“I used to work at the SSC [Superconducting Supercollider]. There was a total lack of realism in selecting a site; it was purely a politically driven decision. DOE thought it ‘cute’ to have a competition and put it in Texas. Starting an entire laboratory over was madness” (Source: F6)*

And:

> *“…best of all was setting up the day-care. DOE said that day-care was a bad idea and not allowed… but we figured out how to get URA [Universities Research Association] to do it and arranged the insurance with no profits or losses allowed, URA was very positive about it... later on DOE decided they liked it and now it’s the model.” (Source: F5)*

Interviewee F11, who previously worked at Fermilab during the Tevatron and subsequently moved to CERN, compared Fermilab to CERN:

> *“Fermilab’s culture has been key. The trouble is the infiltration of bureaucracy and a culture that’s too confrontational, too formalised (since the Tevatron). This hasn't yet happened at CERN. There are still too many layers, too much risk analysis being carried out; what*

> *Fermilab needs to do (nowadays) is let scientists do their thing." (Source: F11)*

These four quotes demonstrate the attitude that the agencies responsible for oversight were perceived as being too interventionist and risk-averse, in contrast to Fermilab's more relaxed attitude toward risk during this time. This attitude was largely tolerated by the previous agency, the Atomic Energy Commission responsible for the oversight of Fermilab, because of the strong associations of particle physics with American defence that I briefly described in Appendix 1 and Section 4.4 (Riordan *et al.*, 2015). This perceived interventionist and formal attitude of the Department of Energy combined with the "aversion to control" that Hoddeson *et al.* (2008) described, led to interviewees regarding the Department of Energy almost as an adversary and even as an impediment to the informal leadership development process that evolved at Fermilab. This informal process is described in Section 4.3.2.

The development of this informal process for leadership development was strongly assisted by the attitude held by all of the directors over Fermilab's history that the laboratory is also a place where individuals learn. Interviewee F5 memorably described the enjoyment Lederman derived from helping others to improve:

> *"Nothing was better for Leon [Lederman] than to recognise potential in others and unlock it. It's a part of all the directors that they also had the teacher mind-set." (Source: F5)*

Both Wilson and Lederman had served as Professors at universities (Hoddeson *et al.*, 2008), indicating that both were capable instructors. Their approach of helping students unlock their potential led to the process of informal leadership development that I describe in Section 4.3.2. Interviewee F3, who led a Fermilab division for many years, shared a similar perspective with Lederman that leaders should develop future talent, demonstrating that this is not an attitude limited to just Wilson and Lederman:

> *"It's not about the leader; it's about allowing people to unlock their potential. It's about facilitating, compromising, going through a process, but most importantly it's about trust… Don't make it all about you." (Source: F3)*

4.3.2 - Leadership development at Fermilab

At Fermilab there appeared to be no active programmes for the development of leadership during the period under investigation. Instead, a laissez-faire attitude existed where senior leaders seemed to assume that scientific geniuses would overcome all obstacles, both scientific and organisational, and find a way to bring themselves to Fermilab's attention. The interviewees perceived no need to create formal leadership development programmes as the best scientists and therefore leaders would find their own way to Fermilab. This was reflected even by senior leaders, for example Interviewee F1 described Lederman's attitude:

> *[When discussing Lederman] "…he could be very hands-off with individuals as 'the cream rises'… He founded the Illinois Math and Science Academy to find the next Einstein" (Source: F1)*

While leadership may not require a scientist to be the 'next Einstein', the interviewees certainly believed that it required technical competence as a foundation for gaining and maintaining respect, as I discussed in Section 4.2.1. Such an individual may or may not turn out to be a good leader – but without technical competence, they would not be in a position to become a leader at all. It is, however, notable that the two previous quotes appear to be a contradiction. The latter portrays Lederman as taking an active role in teaching, yet the former claims that he was very 'hands-off'. I would argue that there is no contradiction. The discovery of the 'next Einstein' is the first stage in the process, where institutions, such as the one Lederman founded, search for gifted individuals. The second stage occurs when respected individuals such as Lederman help to develop such a gifted individual to help unlock their potential.

Several interviewees even expressed before the interview formally began, as a point of pride, that everything they had achieved in leadership roles had required no formal *management* training. The finding that Fermilab conducted neither management nor leadership-specific training programmes during this time is perhaps unsurprising because many authors within the management of large projects domain have deemed leadership development in particular outside the project scope and therefore unnecessary (Dimitriou *et al.*, 2014). However, the literature relating to technically uncertain projects considers leadership development to be much more important (Elkins and Keller, 2003). As megascience projects appear to be a subcategory of large projects that incorporate the characteristics oftechnologically uncertain projects, my observations suggest that megascience projects suit a large project style of leadership rather than a technologically uncertain one.

Leadership development at Fermilab was occasionally undertaken by an existing leader who chose to cultivate future leaders. Interviewees F5 and F7 below, who were both leaders at Fermilab, describe the attitude toward leadership development:

> *"Some leaders are born, but you can find a lot of leaders provided you know how to extract it out of them. Some are incapable of leadership and don't want to be leaders so it's best to leave them be." (Source: F5)*

And:

> *"When I first arrived at Fermilab, I felt slightly inadequate but I was doing such new things no-one really knew what we were doing. Leadership should be an effort to impress upon everyone that no-one knows [both the answers to research questions and the technologies to total understanding] and even if the experiment fails, you have still made a contribution." (Source: F7)*

However, an informal system of leadership training seems to have developed at Fermilab, which encapsulates how leaders should take responsibility for leadership development. In this process, current leaders quietly identified potential future leaders and allocated them a position where they could gain leadership experience, but also ensuring that their future scientific career would not be damaged by a failure to lead. According to a human resources specialist, Interviewee F5, this took the form of a temporary appointment as a section leader for approximately two years:

> *"Even Bob [Wilson] and Leon [Lederman] ran a section; the deal was that you ran it for two years and then go back to experiments. This meant that I always had someone new to teach" (Source: F5)*

As there were no leadership development programmes, this was the method by which Fermilab evolved training provision. Furthermore, all of the six interviewees who commented on the effect of formal leadership training believed that leadership training could not create leaders from nothing. Interviewee F8 illustrates the view held by these six interviewees that leadership is a response to external stimuli:

> *"Leadership is a learned response; you're not born a leader. It's a response to the environment but it can only intensify what's already there." (Source: F8)*

The nature of this environment was harder to determine. However, Interviewees F1 and F11 spoke about their experiences and suggested that the stimulus to intensify leadership could be practical experience:

> *"Genes and experiences in combination. I don't think they're born; one can have the right tendencies but you have to have the right experiences to unlock any potential you have." (Source: F1)*

And:

> *"…Sam Walton [The founder of the supermarket chain Wal-Mart] once said that that the key to success is making good decisions, which came from experience. And the way to gain that experience came from making bad decisions, so there's some merit to say you learn by doing." (Source: F11)*

These quotes demonstrate the perception held by six interviewees that leadership forms over extended periods due to a combination of innate skill and experience. The experiences develop an individual who had the innate skill, and it is the one of the responsibilities of leaders to identify and provide such experiences. Effectively the interviewees argued that leaders are born with the potential, but require a leadership apprenticeship developed by a mentor to realise that potential.

4.4 - Tailoring the selection of different leaders to phases of the project

This section discusses unexpected insights provided by interviewees, which reveal the peculiarities of leading megascience projects. In particular, the respondents' opinions and observations on the characteristics and styles of leadership unintentionally exposed the view that each phase of the development of Fermilab needed a different kind of leader for a number of reasons. These are discussed below. In this case study, I primarily focus on the characteristics of the directors as individuals. I consider the issue in more general terms in Section 6.4, which draws together similar findings from both Fermilab and CERN on this topic.

In their historical study, Hoddeson and Kolb (2003) observed changes at Fermilab between the first two directors, namely Robert Wilson and Leon Lederman. This was due both to differences in their personal leadership style and to external factors in the funding environment. Under Wilson, Fermilab was characterised by a frugal attitude to science, where machines were constructed with the intention of maximising technical parameters even at the cost of reliability. The Atomic Energy Commission, which administered Fermilab during its early years, even drew its staff from the scientific community (Hoddeson *et al.*, 2008). This meant that the US government often approved new projects based on technical novelty (Hoddeson *et al.*, 2008). However, Hoddeson *et al.* (2008) described how shifts in the political environment made Wilson unsuitable for engagement with the 1970s budget-conscious stakeholders who would not approve projects purely because of the technology but emphasised cost control and tying new investments into strategic energy needs.

These shifts, described in Appendix 1, as the national laboratories moved from being overseen by the 'Atomic Energy Commission', to the 'Energy Research and Development Administration', and finally under the 'Department of Energy' coincided with deep cultural change in attitudes to science. This was also accompanied by changing political priorities. Particle physics had long been associated with American defence, particularly the Manhattan Project to develop the atomic bomb - particle physicists possessed extensive expertise in this field (Wilson, 1970; Wilson, 1977; Hughes, 2002). Riordan *et al*. (2015) linked the declining importance of particle physics with the improvement of relations between the US and Soviet Union in the 1970s, often referred to as 'détente'. Therefore particle physics was deemed a lower priority and forced to compete for funding with other areas (Riordan *et al.*, 2015).

However, Wilson's ability to convince people to come together to help him achieve his goals for the laboratory made him ideal for the initial construction of the laboratory, where there would have been many new employees who could be unified under the umbrella of his vision. Likewise, Wilson's charisma allowed him to persuade people to help him achieve goals even when it should not have been feasible. In the words of Interviewee F5:

> *"Bob [Wilson] was a leader and a father figure… As his leaving gift he built a sculpture and had welders teach him how to weld, even though he wasn't in the union; he was just so nice people wanted to help him. You even needed his approval to cut down trees on-site as he wanted to re-create the frontier." (Source: F5)*

However, as demonstrated below, Interviewee F11 described Wilson as having an attitude in which novel technology in itself justified investment. This was not shared by the Department of Energy, which had a mission to meet US energy needs and wanted to incorporate greater levels of cost control and accountability into the administration of the national laboratories (Hoddeson *et al.*, 2008). This gulf in attitudes may have made Wilson a less appropriate negotiator with the Department of Energy during this time:

> *"Now Bob [Wilson] was forceful, always pushing people to do more. He was the best project initiator but not the best listener… Despite his forceful nature, he was very laissez-faire when it came to other things." (Source: F11)*

After the departure of Wilson, a new Fermilab director was selected, Leon Lederman, originally from Columbia University. The interviewees observed a substantial difference between Wilson and Lederman. Interviewee F5 best described the change from Wilson to Lederman:

> *"When you dealt with Leon [Lederman], you expected a performance. He arrived at Fermilab as a renowned experimenter about to win the Nobel Prize. It was a change in leader from a builder to an experimenter. He continued the tradition of all-hands meetings and was a good delegator but also knew how to set guidelines and parameters." (Source: F5)*

This could also represent a shift in leadership style from the somewhat more authoritarian Wilson to a democratic Lederman, while transformational characteristics remained. This distinction between the first director, Wilson, as a 'builder' who was ideally suited to creating an institution and the second director, Lederman, as an 'experimenter' who could take an existing institution and develop it, was further developed by Interviewees F4 and F10:

> *"Bob [Wilson] would build with the assumption that if you build it, then the experimental ideas will come. His [Wilson's] main metric for measuring success was machine performance… Leon [Lederman] had ideas about how to experiment on it while building." (Source: F4)*

This is also borne out by events – it was Lederman who proposed the concepts that would underlie Fermilab *and* the SSC, namely the 'truly national laboratory' and the 'machine in the desert' respectively (Lederman, 1963; Lederman, 1982). But in neither case was Lederman selected to lead the efforts to create these laboratories (Hoddeson *et al.*, 2008; Riordan *et al.*, 2015). Whereas Interviewee F10 described how Lederman, although not the builder of an institution, understood how to run a laboratory to incentivise many collaborations to conduct their experiments at Fermilab:

> *"Leon [Lederman] wasn't a manager but he really knew how to pump out physics, even then he'd rather talk physics than policy." (Source: F10)*

Interviewee F4 also described Lederman's personality:

> *"He [Lederman] took the Fermilab that Bob [Wilson] built and put it on a course with more focus." (Source: F4)*

These quotes demonstrate how Lederman had his own particular style, which he later used to secure the funding for the Tevatron. This included greater focus; Lederman devoted the entire laboratory toward building the Tevatron after having to make up a US$5million shortfall:

> *"…he [Lederman] had to grovel, which really convinced Leon [Lederman] that Tevatron had to be finished before anything else could start." (Source: F2)*

One important stage during Lederman's tenure, while Fermilab sought to secure the funding to construct the Tevatron, was identified by Hoddeson *et al. (2008)* in a June 1979 New York Times editorial. In this editorial, American scientific leadership was described as being at risk unless the US could make specific "vitally important" new discoveries such as the W and Z bosons (Browne, 1979). Considering Lederman's decision to support the Tevatron was taken in October 1978 at the 'Saturday morning shootout' which precluded being part of this race, it seems odd that the New York Times article described the hunt as a race between Fermilab and CERN when Fermilab was about to focus on accelerator construction rather than experimentation (Hoddeson *et al.*, 2008). It is only much later in the article that the limited ability of Fermilab to contribute is acknowledged. This raises the possibility that Lederman intended to exploit this article when later lobbying the Department of Energy.

These observations suggest that directors play vital roles in discrete phases in the life of a megascience project. Wilson conceived the concept of the Tevatron, guided this idea through its early life and made important technical decisions. However, Wilson was not able to convince the Department of Energy to release the funds needed to complete the construction phase. During the Wilson era, the director had to be responsible for creating an institution and basic facilities based on his own vision. Therefore, it was not surprising that Wilson may have shown authoritarian tendencies during this time, as he would have played a key role in realising his vision. Lederman could better engage with the stakeholders to secure funding and command the confidence of budget-conscious government oversight agencies. Fermilab, as an institution, did not account for this possibility, with senior leaders such as directors, effectively serving as long as they wished until external factors brought about a change. In the case of Fermilab, this external factor was the refusal of the US Government to release funds. I discuss the finding, that the selection of various senior leaders was tailored to suit the phase-specific needs of the project, in Section 6.4.

4.5 - Summary

In this chapter, I presented the findings from the first case study. In relation to the first of the research questions, namely “what are the characteristics of those who lead megascience projects”, the fieldwork found that technical competence was deemed the most important characteristic of a leader in the Tevatron. This technical competence was used as a means to gain and retain the respect of the team, from which the leader could derive authority. Although there was a suspicion of managers at Fermilab, a community of associate directors and project managers in middle management roles existed to help the senior leader (director) realise their vision for the laboratory. These middle managers adopted the transactional leadership style, particularly at the final stages of their respective project. However, this was accompanied by a respect for the team as the scientists working on the Tevatron were extremely intelligent and it was considered unwise to demean them. Finally, although the interviewees indicated a profound dislike of authoritarian leadership, they did acknowledge that it is an effective way of achieving change. In this way, leadership manifested in most of the Tevatron projects in a way similar to that described in the large project literature, with charisma also acting as a tool to inspire teams to achieve challenging goals. Although the interviewees held a strong affinity for democratic leadership, they still argued that democracy had limits and there existed situations in which the leader (in this case Lederman) must take responsibility for key decisions and ‘guide’ the democracy to what they deemed the correct decision. Such a situation occurred during Tevatron I, which was originally managed as a project with a very high level of technical uncertainty with multiple technical solutions under investigation, leading to extended timelines. Eventually Lederman made the decision unilaterally to stop further debate. It can even be useful for a leader to exploit the rhetoric and symbolism of democracy while in reality controlling decision-making; this is addressed in Section 6.2.6.

In relation to the second and third research questions, which were “Where were their leadership skills developed?”, and “How were their leadership skills developed?”, the findings from this case study indicate that future leaders were developed by their own supervisors. On this basis, leaders act to develop individual team members while respecting team autonomy and any emergent leaders in the team would be developed by allocating them a temporary position where failure would not permanently damage their future career prospects. Such a practice evolved in response to a general suspicion of formal leadership training programmes at Fermilab. In this case, the *where* and *how* leadership was developed at Fermilab is usually in the form of specific section leadership positions, designed to give individuals with specific innate leadership characteristics the experience to realise their potential.

A final key finding from this case study has been the conclusion that the two laboratory directors were both selected by the trustees of the laboratory in part to meet the phase-specific needs of the project. Wilson formulated both a vision for Fermilab (the laboratory) and the Tevatron. After a change in director, Lederman managed to take the necessary measures to get the Tevatron constructed. While Wilson was not able to secure funding for the Tevatron, it is likewise likely that Lederman may not have been able to come up with Wilson’s rich and detailed founding vision for Fermilab. The change in director proved rather problematic because external actors drove it, namely when the US Department of Energy provided what was deemed insufficient funding for the Tevatron to move from the R&D phase to the construction phase. This damaged relations between the laboratory and the Department of Energy, with the suspicion still an ongoing issue at Fermilab even today. While Lederman's primary task was to get the Tevatron approved by the US government, once this was complete there was no change in director to an alternative who could best support the construction of the Tevatron. However, Lederman still represented the change in skillset between getting the Tevatron approved and constructed by heavily delegating the construction to appointed project managers. These findings are discussed in more general terms in Section 6.4.

5 – Case Study 2 – The Large Hadron Collider (LHC) at CERN

This case study draws on primary archival and interview research conducted together for this thesis and supplemented with relevant secondary literature, to analyse and discuss the leadership findings in the case of the Large Hadron Collider (LHC) at CERN.[32] It seeks to answer the three research questions set out in Section 2.6. Section 5.1 comprises a brief introduction to CERN and the LHC. Section 5.2 explores the findings to identify the answers to the first question, which related to the characteristics of leaders in megascience projects. Section 5.3 sets out the findings in relation to the second and third research questions, which are to understand the nature of leadership development at CERN. Section 5.4 explores the unexpected but important observation that the selection of Directors-General could be partly tailored to suit the phase-specific needs of the project.[33] Finally, Section 5.5 summarises the findings from this chapter, which I further discuss in Chapter 6.

During the fieldwork, I was fortunate to be granted unique access to archival documentation, which is usually restricted for 30 years after internal publication. This documentation covered a number of highly relevant topics, including Director-General selection procedures and the design studies for the LHC. These documents did not directly discuss the concept of leadership, but they provided an insight into the project lifetime and any then-existing procedures for leader selection. The purpose of the archival research was primarily to identify key individuals and project decisions that would inform the interview questions. During the fieldwork, I also interviewed 15 individuals representing a broad cross-section of the CERN accelerator and experimental communities.[34] Two interviewees from the Tevatron fieldwork also spent time at CERN during this period and offered a comparable perspective on both their experiences of leadership and the operation of the two laboratories.

5.1 - CERN: background

CERN – the European Council for Nuclear Research (officially the *Conseil Européen pour la Recherche Nucléaire*) was originally the name given to a provisional council formed by several European countries seeking to rebuild European nuclear physics

[32] The Large Hadron Collider is often referred to by the acronym LHC.

[33] Please note that referral to the Fermilab director in lower-case and the CERN Director-General in upper-case follows the conventions used by the respective laboratories.

[34] A copy of the consent form and interview script is available in Appendix 2.

following the Second World War (Hermann *et al.*, 1987a). In the aftermath of the Second World War, nuclear physics offered the possibility to improve living standards but it carried significant financial requirements (Hermann *et al.*, 1987a). This council aimed to realise a dream held by many senior scientific figures, several of whom served on this council, which was to create a pan-European laboratory where nuclear scientists could collaborate while sharing these costs (Hermann *et al.*, 1987b; Hermann *et al.*, 1987a). This acronym CERN was later applied to the laboratory out of a combination of habit and ease of pronunciation (Hermann *et al.*, 1987a).[35] Although the original intention of the provisional Council was to investigate nuclear physics, particle physics emerged as a distinct field in its own right during the latter part of the 1950s (Hermann *et al.*, 1987a). This new field explored the fundamental building blocks that make up protons, neutrons, and other subatomic particles; an appealing subject for scientists seeking to answer questions about the nature of the universe (Hermann *et al.*, 1987a; Perkins, 2000).

The governance structure comprises a council as the supreme decision-making body of the laboratory and a management team responsible for implementing strategy. The council, called the CERN Council, is composed of member state representatives who set strategy and select the laboratory's management (Smith, 2007). The Council only meets occasionally; there are two types of meeting. These meetings can be either open or closed sessions: closed sessions give the Council the privacy to discuss key issues frankly before presenting a united front in open sessions to make final decisions. The CERN management team includes heads of department and a Director-General who jointly implement day-to-day decisions. The tradition is that a CERN Director-General and the executive team serve a single five year term, although there have been exceptions to this rule (Hermann *et al.*, 1987a; Hermann *et al.*, 1987b).[36]

Since its foundation in 1954, the CERN laboratory (which will now be referred to simply as CERN) has constructed a variety of experimental facilities, often re-purposing previous accelerators into the supporting infrastructure for new ones, as noted by various authors

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[35] This does create a minor discrepancy in branding as the council 'CERN' was dissolved in 1954 and the official name of the laboratory is the *Organisation Européen pour la Recherche Nucléaire* that would logically make its acronym 'OERN'. Nonetheless, for ease of pronunciation, the laboratory has continued to utilise the 'CERN' title.

[36] I have identified two rare cases when a Director-General served for less than the standard five-year term. The first case was in 1955 when Felix Bloch handed over to Cornelis Bakker to return to his scientific work in the USA. The second case was in 1960 when John Adams served as Acting Director-General for a year following the unexpected death of Cornelis Bakker.

as well as the archival documentation in the following quote (Hermann *et al.*, 1987b; Hermann *et al.*, 1987a; Krige, 1997):

> *"[The proposed LHC] …makes use of existing CERN infrastructure which can provide injection beams at the required characteristics."* *(Source: A Large Hadron Collider in the LEP Tunnel, 1984)*

The LHC is the most recently completed accelerator at CERN, having achieved first beam collisions in 2008 (Smith, 2007; Evans, 2009). Over the LHC project construction lifetime, there were four Directors-General, each serving a five-year term as senior leader of the organisation (Evans, 2009). The first of these, Carlo Rubbia, took charge during the creation of a large hadron collider concept and defended it from competing plans for alternative accelerators, advanced during this period. The second, Christopher Llewellyn-Smith, secured the funding and approval for the LHC from various funding bodies including the CERN Council. The third, Luciano Maiani, oversaw the majority of the construction project and regained the confidence of the CERN Council following doubts over the LHC's financial viability in 2001.[37] The fourth and final Director-General during the construction of the LHC was Robert Aymar. His tenure saw the completion of the LHC.

I chose to distinguish between senior leaders, middle management, and task-focussed leaders on the three level model used by Mumford *et al.* (2007) that I discussed in Section 2.3.2, a model which divides an organisation into senior, mid, and junior levels based on the differing skill requirements. I chose to retain the senior level title but to rename the 'mid' and 'junior' levels as 'middle management' and 'problem-focussed leaders'. For this specific case study, I consider the CERN Directors-General as 'senior leaders' with project leaders and departmental heads as 'middle management'. All leaders below this level are primarily working hands-on with the technology and are thus 'problem-focussed leaders' (see Figure 2 for a diagram illustrating the three level model and CERN's relationship with the Council and the experimental collaborations):

[37] This is analysed for its leadership implications in Section 5.2.1

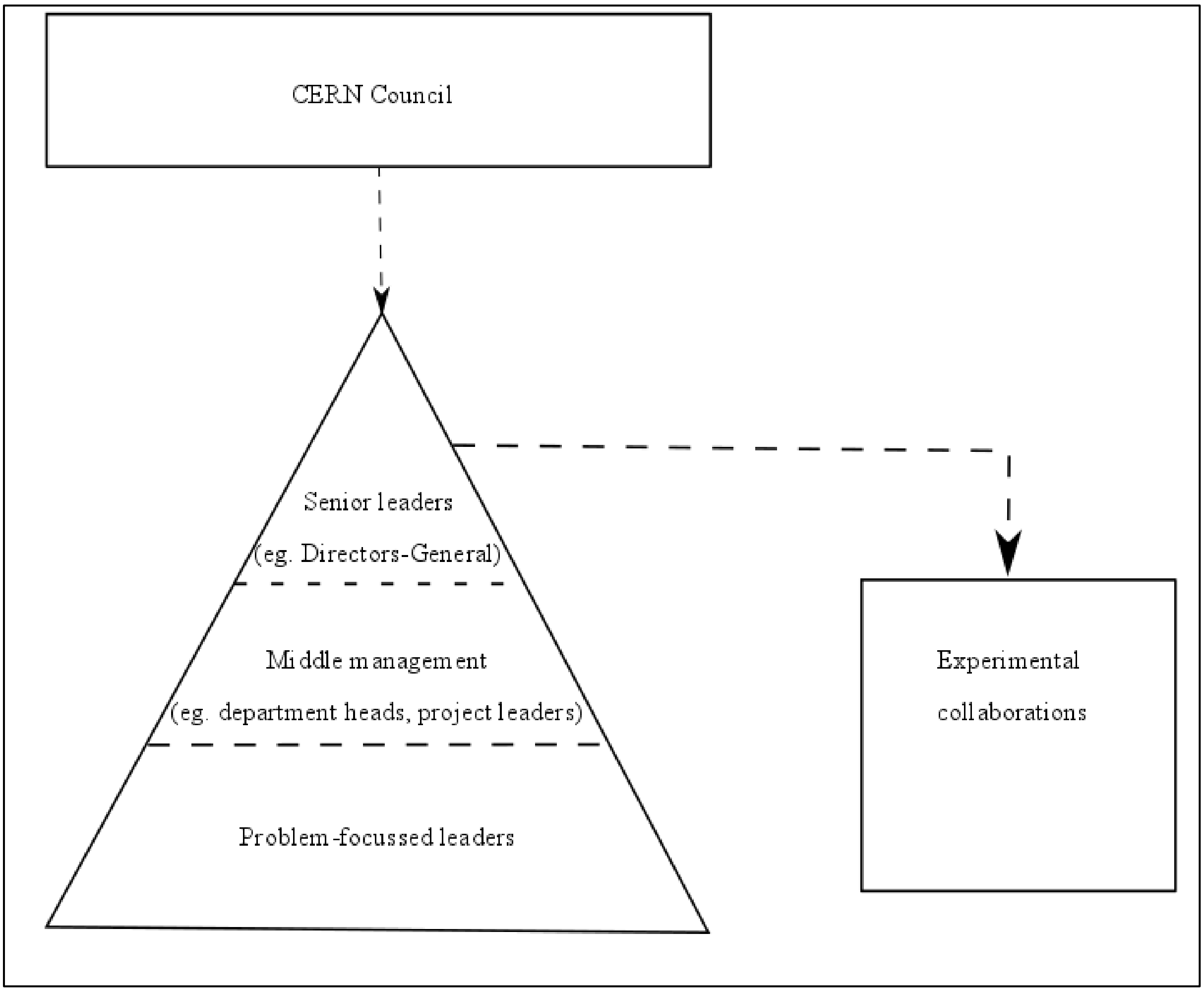

Figure 2: Diagram showing organisational structure of CERN in the context of the model for analysing leadership. Also illustrated is the indirect link between CERN and the experimental collaborations

5.1.1 - The LHC: background

Even as LEP[38], the previous major collider at CERN, was beginning operations in 1989, thoughts had already turned toward the next 'big machine' (Smith, 2007). The quote below discussing CERN's future strategy demonstrates some of the internal atmosphere during this period:

> *"The very successful start-up of the Large Electron Positron (LEP) collider in 1989 here at CERN was the outcome of physics discussions originating more than ten years earlier and leading to a recommendation by the European Committee for Future Accelerators (ECFA) in 1979. Similarly the HERA proton-electron collider had been*

[38] LEP stood for Large Electron-Positron collider, which collided these two types of particles (electrons and positrons). These types of particles (leptons) are fundamental with no underlying structure, so the collisions produce very 'clean' results and are appropriate for making precision measurements.

recommended by ECFA in 1981. It started operations this year in Hamburg and in flight proton-electron collisions were recorded for the first time ever.

It is now time to take decisions for the physics to be studied ten years hence and to aim for an equally successful future.

The shaping of this future is a continuous activity. It is the common endeavour of the international community of the particle physicists, and is debated intensively worldwide." (Source: The LHC and its users: Augustin (1992) CERN/1914 Annex 3)

The LHC emerged as part of a conscious 'world accelerator strategy' in which many physicists worldwide consolidated their research, seeking to build a single facility to conduct a specific type of experimentation and prevent the wasteful duplication of facilities (Riordan *et al.*, 2015). This is in contrast to the Superconducting Super Collider[39], a competing accelerator also pursued during this time, which was presented as a national machine intended to re-establish American leadership in particle physics (Riordan *et al.*, 2015). The inclusion of the LHC as part of a 'joined up' strategy agreed with other members of the International Committee for Future Accelerators (ICFA), an informal grouping of prominent members of the particle physics community, would later prove useful as the scale of the LHC proved too great for CERN member states to fund individually (Smith, 2007; Evans, 2009). This required the second Director-General, Christopher Llewellyn-Smith, to pursue creative financial and diplomatic mechanisms to secure the approval of the LHC. During the early stages of the LHC, CERN understood that the LHC would require project management on a larger scale than anything they had engaged in before. CERN even commissioned a project management report, when seeking to determine just how to manage such a project:

"As a project management task the LHC sets a new challenge for CERN. Yet CERN is not starting from scratch in large project management: the Large Electron Positron Collider [LEP] project has already taught us many practical things which are relevant to the construction of the LHC. Thus, by exploiting this experience with the

[39] Also referred to by the acronym SSC.

> *use of modern methods, the task will be accomplished." (Source: What to be implemented at the early stage of a large-scale project: Bachy and Hameri (1995) LHC Note 315)*

During the project, project management tools such as EVM were introduced because of a budget crisis in 2001; this is relevant to the managerial skills leaders required to effectively exploit these tools which I consider in Section 5.2.2.

The LHC is currently the most powerful synchrotron in the world, with collisions engineered at 13TeV (CERN, 2016).[40] The LHC circulates twin proton beams using a novel arrangement in which both beams use a single magnet system and cryogenic system. Its development necessitated the use of superfluid helium magnets on an extremely large scale, with 27km (17 miles) of magnets installed in the pre-existing LEP tunnel, making it a 'C' class category project according to the Shenhar and Dvir (1996) classification system (See Section 2.4.3). A 'C' class category project is one that incorporates existing technology on a previously unused scale or arrangement (Shenhar and Dvir, 1996). The magnetic and cryogenic systems constituted the most technologically uncertain aspects of the LHC, reflected in the quote below:

> *"LHC is based on superconducting storage rings that will be installed in the LEP tunnel… In view of the fact that the machine will be installed in an existing 27km tunnel… The magnet system contains many key innovative features to reduce cost… the large stored energy within the magnets makes it necessary to develop a sophisticated quench system." (Source: Advanced technology issues in the LHC memo, 1994)*

As the LHC and its associated experiments are still in operation with future upgrades planned, it is not yet possible to provide a final project budget. However, most estimates put the original construction cost, including associated infrastructure upgrades, at approximately 6.5 billion Swiss Francs[41], equivalent to US$6.71 billion (as of May 2017)

[40] It is noted that this 13TeV figure refers to proton-proton collisions. The LHC is also capable of lead ion collisions, which currently take place at 1.38TeV reflecting the much greater mass of lead ions compared to protons.

[41] In CERN documentation, the Swiss Franc is used as the official currency of the laboratory. The acronyms MCHF and BCHF are used to refer to millions and billions of Swiss Francs respectively.

(Lefevre, 2009).[42] At the present time the particle physics community is exploiting the LHC; it is currently in its second 'run'.[43]

The LHC experimental collaborations formed their own structures to build detectors, each led by an elected collaboration spokesperson. New members could easily join, regardless of CERN membership status, and many research laboratories and universities pooled their resources to construct the detectors. These detectors were vast enterprises, with total budgets in the US$500 million range (Evans, 2009; Morgan, 2009). There are currently seven experimental collaborations associated with the LHC (Evans, 2009). I selected two of these collaborations for inclusion in this thesis because of their similar experimental aims. These experiments were ATLAS and CMS, each constructed with the original intention of determining the existence of the then-theorised Higgs boson. The extension of the unit of analysis to include two experimental collaborations offered the opportunity to explore whether there was a difference in leadership style between experimental collaborations and accelerator construction.

5.2 - What are the characteristics of LHC project leaders?

This section is concerned with seeking to answer the first research question in the specific case of the LHC and its associated experiments. During the fieldwork, certain themes emerged during leadership-related discussions with the interviewees. All of the interviewees had served in leadership positions, so they were well-placed to comment on leadership based on their personal experiences of leadership and the identification of future leaders amongst their team. In many cases, the interviewees observed commonalities amongst their colleagues.

5.2.1 - Technical competence

All interviewees described the primacy of technical competence as a determinant of leadership potential in a megascience project. Interviewees C6 and C4 in particular best described the importance of technical competence:

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[42] After the decision by the Swiss Central Bank to stop pegging the Franc to the Euro in January 2015, the US Dollar to Swiss Franc exchange rate did drop substantially, but this new valuation is broadly in line with the 5-year average exchange rate.

[43] The term 'run' refers to a single season of operation at a particular energy. The first LHC run took place at a significantly lower energy before upgrades allowed higher energy collisions in the second run. Likewise, the Tevatron had several runs operating as a fixed target machine and as a collider.

> *"The most important component [of leadership] is technical competency, from which comes respect." (Source: C6)*

And:

> *"A leader has to know more or less the intended direction, choose the right people to be complementary but above all else they must be technically competent." (Source: Interviewee C4)*

These quotes demonstrate that the interviewees perceived that technical competence acts as a foundation for leaders to gain and maintain respect. It also provides a mechanism by which leaders can emerge from small teams as Interviewees C15 and C3 described:

> *"It's quite democratic at the low levels; leadership is very much on a technical basis. [For example] You need electricians working on electrics. Technical skill counts for a lot there." (Source: C15)*

And:

> *"Identify a future leader and you can train them later on. You identify them by technical competency. Give them a chance to show their interest or abilities on a small-scale." (Source: C3)*

Technical competence provides a good foundation for respect when teams are considering very specific problem-focussed tasks. However, senior leaders such as Directors-General, take an overview and may not require such depth of technical competence. I chose to base my distinction between senior leaders, middle management, and task-focussed leaders, based on the three level model used by Mumford *et al.* (2007) that I discussed in Section 2.3.2. This model divides an organisation into senior, mid, and junior levels based on the differing skill requirements. I also chose to retain the senior level title but to rename the 'mid' and 'junior' levels as 'middle management' and 'problem-focussed teamwork' to reflect the true roles at those levels in experimental particle physics. Project leaders and collaboration spokespersons fall into the category of 'middle management', although there is overlap with senior leaders in terms of their skills requirements. Such project and collaboration leaders may need an understanding of how the various systems interface.

Discussions with the interviewees from the accelerator construction generally focussed on the LHC project leader, Lyn Evans. Interviewee C16 described him as follows:

> *"Lyn Evans was very good, had the right qualities… he was the best person for the job. [He was] The only one able to realise LHC conceptually and organisationally." (Source: C16)*

Unfortunately, Interviewee C16 declined to define the 'right qualities' that marked Lyn Evans as being different from other potential project leaders. However, interviewees C11 and C13 did describe Evans' main qualities:

> *"Lyn was forceful, really knew his stuff especially in magnets which is what LHC was all about… a 'grumpy old b****r'* - *there was a lot of forcefulness in his character which we needed to pick amongst a lot of divergent potential [technical] paths." (Source: C11)*

Interviewee C13 described Evans in similar terms:

> *"Lyn Evans did a good job, led by being extremely good at what he did. He knew everything and had a vision of LHC, which wasn't easy at the start. Kept all the science in his head and taught himself when required. The best accelerator physicist and had the technical respect of the community" (Source: C13)*

These quotes underline the perceived importance of technical competence. The need for this as a foundation for respect is not limited to those working directly with the technology. Even these senior leaders in charge of an entire project, organisation, or experiment must command respect in this way, even when total understanding of all the technologies is impossible. In this situation, it is sufficient for the leader to be reasonably competent in most of the technologies but it is imperative that they be fully competent in the most technologically uncertain aspects of the project. In the case of the LHC, this applied to the magnetic and cryogenic systems (Evans, 2009; Evans, 2014). These quotes also demonstrate that the leader of a CERN project has his/her own vision of the project to guide technical choices. In the case of the project leader, the technical competency can also be limited to the key technologies. This is similar to other high technology projects wherein leadership choices are often dictated by key technical factors (Kidder, 1981); this is addressed in Section 6.2.1. However, project leaders must have a broad understanding of all parts of the project. Project leadership is so concerned with understanding the key technologies that the more standardised components of the project could become a major source of issues, as Interviewee C15 suggested:

> *"You'd be amazed that the majority of the issues are low-tech shocks - plumbing, for example." (Source: Interviewee C15)*

This point has been validated through subsequent events which affected LHC operation such as the 2015 short-circuit attributed to debris accumulation and a 2016 incident in which a small rodent chewed through a power cable (Aron, 2015; Aron, 2016). Presumably, project leaders are mainly concerned with ensuring that the most technically uncertain components of the project are proceeding well. However, the less technically uncertain parts of the project, such as the plumbing, are often completely outside the competency of the project leader. How leaders might handle situations where they have no technical competence is considered in Section 5.2.8.

5.2.2 - Management ability

As discussed in Section 2.2.2, many authors have made a distinction between leadership and management, based on the premise that leadership is about revolution while management is about evolution (Bass, 1990). On the other hand, other authors have likened certain leadership styles to management, particularly transactional leadership, which requires managerial skills to realise a transformational leader's vision (Hater and Bass, 1988; Kirkpatrick and Locke, 1996). As discussed in the Tevatron case study, here too it became necessary to understand whether the interviewees also perceived a difference between leadership and management. During the discussion of this question, three interviewees perceived no difference between leadership and management, with an additional interviewee noting that being a manager within CERN requires a strong leadership component (see below). The remaining 12 interviewees did perceive such a difference.

The first group of three interviewees who identified similarities between leadership and management, generally answered the initial question with a simple response, as illustrated by the following quote from Interviewee C1:

> *"Management equals leadership." (Source: C1)*

It proved difficult to initiate any real discussion on the subject with this group as such strong comments indicated there was unlikely to be any nuance to their views. The remaining 12 interviewees formed a second group who identified a difference between management and leadership, although one interviewee claimed that leaders should embody both management and leadership as the quote below from Interviewee C4 illustrates:

> *"To be a manager at CERN, you need technical competency and leadership. 50% of being a CERN manager is leadership" (Source: C4)*

This quote suggests leaders must embody the characteristics of both management and leadership. However, the remaining 12 interviewees viewed it as a symbiotic relationship with both managers and leaders performing vital functions. Interviewee C11 best described this perception with management conducting the vitally important work. Indeed, without a manager, the leader would be unable to achieve their vision:

> *"Leadership delivers a vision, direction and gets people to live that experience. Your commitment to the idea is reflected in them [the team]. Management is important. In the beams department, if the personnel management and budgets are done well, it's a good basis for delivery" (Source: C11)*

Interviewees C6 and C12 suggested that leadership focused on construction projects while management was about learning how to exploit existing assets to optimal levels. This articulation of the management-leadership difference using train metaphors was popular:

> *"Some roles need managerial skills but not leadership. The Physics Department runs a smooth operation but it doesn't lead. That's the job of research. Management keeps the trains running on time but leadership builds the train line" (Source: C6)*

And:

> *"Yes there's a leadership-management difference. Leadership is about inspiring. Project leaders need to be leaders. Management keeps the trains running on time." (Source: C12)*

This discussion revealed that, while most of the interviewees perceive a difference between management and leadership, a middle management leader such as a CERN department leader must frequently embody the skills of both a leader and a manager. However, all of the interviewees said that the most effective CERN leaders understood this and carefully selected managers in their team to fill such skill gaps, as the quotes below indicate:

> *"The ISR [previous CERN collider] project leader was technically good but not such a great manager. Fortunately, you can select your team to fill in your own personal gaps." (Source: Interviewee C12)*

And:

> *"[One particularly good leader] …knew their science for most part. His real skill was in his sheer breadth of knowledge and using deputies to fill in his gaps." (Source: Interviewee C9)*

These quotes illustrate that the most effective CERN leaders are able to recognise their own limitations and select managers to conduct important underlying tasks, such as proposing and managing budgets that are required to ensure smooth operation. However, in the case of the LHC the project leader, Lyn Evans, had to both lead and manage the project and he carefully selected the rest of the project management team along these same lines. As described earlier in Section 5.2.1, Lyn Evans had his own vision of the project, which inspired those working for LHC. He was also required to act as a manager to bring the project to completion and maintain the trust of the CERN Council, a key issue discussed in Section 5.2.3. While various change control systems existed, two interviewees who served as leaders during the LHC project described the importance of the 'Earned Value Management' tracking system.[44] The EVM system offered a well-known and relatively easy-to-use solution. It also enabled the production of visual graphs that provided easily digestible information to stakeholders such as the CERN Council, proving important for maintaining their trust. As part of the fieldwork, I received temporary access to some of these graphs and it was immediately possible to track the project. These graphs were comprised of three data points – the expected value (i.e. the projected cost in the budget), the earned value (i.e. the value of work completed until that point) and the actual cost. Toward the end, the project the Earned Value should equal the Planned Value. Although the concepts underlying EVM can be traced back to the 19th Century, EVM was first developed in the 1960s and rolled out across many US federal projects in the mid-1990s after the SSC collapse (Kwak and Anbari, 2012). The 2001

[44] Earned Value Management is also known by the acronym EVM.

budget crisis discussed in Section 5.4.3 provided the impetus to apply EVM to the LHC project. Two senior interviewees described the importance of EVM. Interviewee C1's quote describes both how EVM works and its introduction to the LHC:

> *"We brought EVM into Europe for the first time. Ever since the SSC, the DOE insisted on EVM. EVM breaks everything down into pieces three months long with an assigned value. Once EVM is set up, which involves a lot of work at the start, all you do is report back. At first, the estimates are muddy but improve as time goes on. CERN Council would understand spending too much within certain limits. During 2001 budget crisis when there was a substantial gap in the LHC budget of the order of one billion [Swiss Francs] we had a 200 million [Swiss Francs] overspend by the end, [so] it was very important for CERN to implement EVM… Produces clear and easily understandable reports and it was adapted from defence contractors. Very easy to see what's happening." (Source: C1)*

This demonstrates that middle management leaders had to implement specific systems and protocols in order to track the LHC project. Implementing the EVM system required the LHC project management team to have necessary management ability.

5.2.3 - Trustworthiness

CERN is an organisation with a core of around 2000 members of staff and a user community many times larger (Krige, 1997). The experimental collaborations are even larger, almost double the size of CERN's workforce, with around 3500 in each collaboration (Evans, 2009). As the output of a team is ultimately the responsibility of the leader, a leader traditionally can use the prospect of reward or punishment to induce compliance (Bass and Avolio, 1993). However, this was not apparent at CERN; instead, eight interviewees described the importance of trust. Interviewee C7, who described the need for trust between all parties, perhaps gave the most evocative quote:

> *"Optimism and assurance are needed quite frequently though. Like conducting an orchestra... Everyone has to focus on their part and keep faith with the rest; otherwise they can't do their own role well." (Source: C7)*

This quote demonstrates the importance of trust, which binds together the entire project as a mutual partnership with everyone cooperating to achieve certain goals. This applies to both the experimental collaborations and the LHC construction, as Interviewee C1's quote demonstrates:

> *"There's a certain amount of relying on collaborators, so you have to do the background work and pick good ones. With the civil engineering, we had to rely on total outsiders and trust their judgement." (Source: C1)*

With this trust comes the risk that this trust can be lost. This fact can be utilised by leaders, who may not be in a position to punish individuals, to get people to keep their promises. Interviewee C1, who worked on the LHC construction project, described using trust as a tool to get collaborators to keep their promises:

> *"Dealing with non-member states was difficult. Much more like building experimental collaborations but you had a little influence over them. Had to use peer pressure in the form of meetings held on-site, making them fly in from wherever in the world they were. It worked!" (Source: C1)*

At problem-focussed levels, this trust may come from a team leader. When Interviewee C7 was given a substantial responsibility in a previous CERN experiment and was trusted to do well, he felt genuinely valued:

> *"UA2 management was outstanding. I had no previous accelerator experience but was given a key role in accelerator design. Great confidence was placed in me and I repaid it. I would do anything to not lose their confidence in me." (Source: C7)*

This quote demonstrates how a single individual may feel after receiving the trust of the community; this trust acts as a motivational factor. When an individual is given the trust of the CERN community, they generally work hard to demonstrate to the community that they were worthy of that trust. There is an additional importance to this type of relationship at senior levels, as leaders such as the Director-General or a project leader must maintain the trust of stakeholders, especially the CERN Council. In this case, the

Council effectively acts as a representative of the user community. Interviewee C14, a senior leader at CERN, described the importance of senior leaders in maintaining trust:

> *"[On key components of being a leader] Gaining and maintaining the confidence of the community, while maintaining credibility with external stakeholders." (Source: C14)*

The possible consequences of a crisis affecting the confidence of the Council are interesting, and the CERN Council expressed some concern over the financial viability of the LHC in 2001 during a budget crisis. The measures taken by CERN management to demonstrate to the Council that the LHC project was under control in order to maintain their trust are described in Sections 5.2.2 and 5.4.3. However, the interviewees viewed the CERN Council as trusting in a leader's ability to achieve goals and the Council could act to help them as necessary. Therefore, the interviewees perceived the process of LHC construction as a partnership between them and the CERN Council, with the Council representing stakeholders but acting to facilitate the project rather than trying to impose their will.

One important question is whether this trust means that a 'partnership' stage of leader-member exchange, as I described in Section 2.3.4, has been achieved (Graen *et al.*, 1982). The 'partnership' stage occurs when the relationship is based on mutual trust and both parties believe the other will go beyond the contractual and formal job requirements (Graen *et al.*, 1982). In the case of the LHC and its associated experiments, this has been achieved due to the underlying belief that even the CERN Council is working toward the same goals as the rest of the laboratory. The quotes below demonstrate the support given by the Council (although in some instances this may have been 'tolerance') of the CERN management's proposals:

> *"The CERN Council would understand spending too much provided it was within reasonable limits." (Source: C1)*

And:

> *"[When discussing the 2001 budget crisis] We took out a European Investment Bank loan… of 350 million Euros repaid after 9 years. The CERN Council had to guarantee funding. In June 2002, the CERN Council approved the new costing plan with costs. In return for the*

> *approval and the guarantees we introduced a new cost monitoring system [EVM]." (Source: C16)*

This demonstrates that, although the CERN Council and CERN management were working together toward constructing the LHC, the CERN Council did not give management a completely free rein. Instead, the Council chose to trust but verify CERN management's proposals through the introduction of new tracking methods.

5.2.4 - Selflessness

All interviewees went to great lengths to describe the equality and the trust in the relationship between the leader and the rest of the team. The leader acts in a way that would ensure a good outcome for the team and the project without regard to their personal glory. The interviewees usually described this as saying that egos were bad for everyone and this is exemplified by Interviewee C5's quote:

> *"Forget ego. You need the desire to be a leader but too much ego leads to a danger for science. The main goal is science; if you forget about science it's bad for the team and you lose your achievements." (Source: C5)*

Although other interviewees also provided memorable quotes such as Interviewee C11 and C16:

> *"[When discussing the most important components of leaders] [The] most important attributes are to respect egos but don't allow them to dominate. Skill to allow recognition [of others while you] take the s*** and share the praise." (Source: C11)*

And:

> *"The main obstacle to being an effective leader is ego" (Source: C16)*

One practical example of a leader putting the project before themselves came during the 2008 LHC magnet crisis, where a helium leak caused mechanical damage to the magnets. Interviewee C2 described the atmosphere at CERN during this time:

> *"After the quench[45] the atmosphere changed; there was a period of shock followed by depression." (Source: C2)*

Interviewee C12 described it as being like a death within the family:

> *"We had to go through the mourning period before we could analyse what went wrong" (Source: C12)*

These quotes illustrate the troubled atmosphere at CERN during this time, with many theories offered to explain what caused the quench (Bajko *et al.*, 2009; Rossi, 2010). While there were some allegations from the interviewees that CERN Management wanted a 'quick fix', this was resisted by the Accelerators Department. The head of that department, Steve Myers, subsequently held a workshop at a neutral remote location with all relevant parties to determine exactly what had happened, how to repair the components, and how to prevent a repeat event. This proved to be a great success as the remote nature of the event created an intellectual distance for critical analysis, and it became incorporated into annual strategy discussions, as described by Interviewee C12:

> *"Now we have an annual Chamonix workshop to bounce off all problems from the previous year and project what's next to get buy-in, usually in January" (Source: C12)*

This demonstrates that the leader must ignore all egos, including their own, putting the project and the machine first. This may even result in a leader having to resist pressure from a senior leader, specifically the Director-General. I consider the attitudes of the interviewees towards that particular Director-General and his policies in Section 5.4.4.

5.2.5 - Leadership styles

During the interviews, I supplied the interviewees with information about the five leadership styles described in Section 2.2, and then asked them to discuss how applicable each leadership style was to megascience projects. (To remind the reader, these leadership styles are transformational, transactional, authoritarian, laissez-faire and democratic.) During these discussions, interviewees spoke of their experiences at CERN, at other

[45] During the quench incident, an electrical fault created a hole in the liquid helium cryostat system, causing a liquid helium leak. During this leak the liquid helium, rapidly increased in temperature and changed in state from a liquid to a gas, therefore causing a massive increase in pressure. This pressure increase caused significant damage to several magnets. Unfortunately, the quench incident took place just after the handover from project leadership control to CERN departments for operation so no archival documentation was available.

laboratories and occasionally about their doctoral training. Their experiences were categorised according to these five leadership styles. Their comments helped me to identify additional characteristics of leaders during the LHC.

5.2.6 - Transformational leadership

As the literature discussed in Section 2.2.1 indicated, the key components of transformational leadership are the communication and implementation of a vision accompanied by a charismatic communication style (Bass, 1990). All interviewees described how transformational leadership was highly appropriate to megascience projects at specific points in the project lifetime. The interviewees often described Carlo Rubbia as a transformational leader, a point considered further below.

5.2.6.1 - The communication, inspiration, and implementation of a vision

Every interviewee considered a vision to be a fundamental component of leadership, as Interviewee C13's quote illustrates:

> *"Being a leader is about vision and setting a direction." (Source: C13)*

However, it was not deemed necessary for a leader to always devise their own vision as one may already exist higher up the organisational structure, in which case the communication of the vision increases in importance as a way of 'selling' the vision to stakeholders, as Interviewee C14 noted:

> *"Being a leader is about having a vision which wasn't needed in my case but I could articulate it… Sell the vision to get funding while finishing what came before." (Source: C14)*

As this also suggests, such a vision can extend through the tenures of several Directors-General, with subsequent individuals recruited based on their ability to realise the original vision. In the case of the LHC, three interviewees described the vision as originating from Carlo Rubbia. The quotes below demonstrate that Rubbia had a vision of the LHC and was able to unify the laboratory around it:

> *"Carlo Rubbia had the vision back then" (Source: C11)*

And:

> *"Carlo Rubbia had to launch and defend LHC. But he was credible and people just followed him" (Source: C16)*

And:

> *"Carlo Rubbia… really developed CERN, kept the LHC dream alive" (Source: C6)*

As Rubbia's tenure finished relatively early in the LHC's life, it fell to subsequent Directors-General to communicate and implement his vision. The interviewees held varying attitudes about whether these subsequent Directors-General developed their own vision or adjusted Rubbia's to make it more feasible. This idea is explored in Section 5.4. There was disagreement over whether the laboratory required a vision at all times, with the interviewees evenly divided into two groups. One group said that once a vision is complete, a laboratory can 'tick over' whilst upgrades are completed and data is produced, as Interviewee C11 best stated:

> *"CERN doesn't really need vision right now; it's just ticking along. But for us that's pushing the boundaries of human knowledge and technical possibilities" (Source: C11)*

This interpretation would mean that, for a few years following the realisation of a vision, CERN could focus on fully exploiting the completed accelerator rather than immediately starting to determine the characteristics of the 'next big machine'. Another group of five interviewees, who tended to have occupied senior leadership positions, felt that once a project is complete, the community rapidly needs a new vision to preclude migration to other laboratories, as Interviewee C6 claimed:

> *"Building is easy as it's exciting. The first running in 2010 was fun but keeping something running is much harder. Like getting a Ferrari, buying is exciting but maintenance is boring. The interest for me is in building… people always want a new challenge" (Source: C6)*

It is more likely that the CERN community prefers the latter option, namely the rapid development for a new vision, for the reasons considered above. This would explain why the LHC concept was devised so soon after the completion of the LEP, and why CERN is now moving rapidly toward substantially upgrading LHC under the title 'the High Luminosity LHC' (Rossi and Brüning, 2012).[46] This continues a long trend observed by

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[46] Also referred to varyingly as HiLumi LHC or HL-LHC, it is currently on schedule to commence operations in 2026.

previous literature that CERN begins planning for the next accelerator as a current project comes close to completion (Hermann *et al.*, 1987b; Hermann *et al.*, 1987a; Krige, 1997).

As the literature reviewed in Section 2.2.1 indicates, a charismatic communication style is generally exhibited by the expression of high expectations of followers and confidence in their abilities to meet those expectations (Shamir *et al.*, 1993). None of the interviewees described any particular individual as being particularly charismatic in their communications. Charisma was instead described in prescriptive terms by six interviewees as a way of keeping a team satisfied without really identifying the concept, as exemplified by Interviewee C9:

> *"Be charismatic and friendly so people will approach you with their opinions." (Source: C9)*

On the other hand, Interviewee C5 described charisma as a way of identifying future leadership talent, making a novel link between problem solving and charisma:

> *"When people have a problem and it's difficult, the future leaders accept and enjoy the challenge. That charisma is easy to see. The challenge excites them" (Source: C5)*

These vague descriptions from the interviewees made it rather difficult for me to define charisma in the CERN context. This is likely because charisma is a phenomenon that is difficult for non-experts to describe in specific terms, but can readily be identified when it is observed (Conger and Kanungo, 1994). This could also be a reflection of CERN's international workforce. As noted in Section 2.2.1, charisma is a highly situated phenomenon and the observer's definition of charismatic behaviour can be influenced by national culture (Conger and Kanungo, 1994). As CERN has a very diverse workforce, it is likely that my interviewees' definition of charisma is ill-defined and comprises a combination of these nationally situated definitions of charisma, but one that has yet to really develop beyond a slightly confusing combination of these national definitions. Although there exists some research into the relationship between national culture and charisma, these studies tend to conclude that national culture can affect what behaviours are considered charismatic rather than seeking to understanding which charismatic behaviours are affected (Snyder, 1979; Weierter *et al.*, 1997). It is also likely that the CERN culture of highly motivated and focussed individuals, which I discussed in Section

5.3.1, contributed to the uncertainty of the interviewees over the definition of charisma. When teams are already highly motivated to achieve a vision, one might reasonably question the need for charisma to inspire these teams. However, charisma will still have some value in terms of uniting teams under common values. This will also need to be accompanied by actions to re-inforce this message. I discuss this further in Chapter 6.

From these discussions on transformational leadership, I firstly determined that a vision is extremely important for the first senior leader (specifically a Director-General) when a new collider is being considered. After the creation of the vision, subsequent senior leaders only make minor adjustments as they seek to realise it. Leaders elsewhere in the organisation such as middle managers and problem-focussed leaders do not require their own vision as they are also seeking to deliver on the senior leader's vision. Despite the lack of a clear definition of charisma offered by the interviewees, but referred to by many of them, charisma is a characteristic of leaders in megascience projects.

5.2.7 - Transactional leadership

As discussed in Section 2.2.2, transactional leaders work within existing cultures to achieve change, and only intervene in tasks when they deviate from expectations (Bass and Avolio, 1993). Transactional leaders have various tools to ensure compliance such as the prospect of reward or punishment (Bass and Avolio, 1993). The interviewees were divided on the utility of transactional leadership, with this division broadly corresponding to whether the interviewee was in accelerator construction or an experimental collaboration. The ten interviewees who perceived some utility and who came from accelerator construction said that it was context-dependent. Interviewee C13 discussed how:

> *"Everyone has a proportion of characteristics and a mix that makes them good leaders. There are the slightly different mixes and they modify the mix as needed. You need a certain level of transactional leadership to get agreements." (Source: C13)*

Earlier in the interview, Interviewee C13 described how he intervened with teams only when certain issues became apparent. This practice of avoiding intervention unless problems become apparent is a core principle of management by exception, which I identified in Section 2.2.2 as an important trait of transactional leadership. Other leadership styles generally do not pursue such a policy, for example an authoritarian leader would be in a position of constantly intervening, irrespective of whether there was a challenge to address or not (Bass, 1990). In other cases, Interviewee C13 chose to allow teams to determine for themselves how best to achieve their goals, only intervening when difficulties occurred:

> *"I'm so busy I choose to let the team run without tweaking and make minor adjustments when something becomes a bottleneck... When the system is in a less steady state, it needs continuous improvement, [and] the department effectively runs itself... Leaders have to take system-wide decisions as only they can understand what the effect will be elsewhere and it's [their] responsibility." (Source: C13)*

This suggests that some leaders may give the impression to teams that they are laissez-faire, considered in detail in Section 5.2.8, when the reality is that they are focussed on securing adequate provision for their team and building support elsewhere within the organisation. The interviewees also regarded transactional leadership as necessary at late stages of the accelerator project when the technical challenges have largely been solved, as Interviewee C15's quote demonstrates:

> *"Become more transactional and democratic toward the end stages. When you see something slipping, try to understand why." (Source: C15)*

In contrast, in the case of experimental collaborations, there was an assumption that transactional leadership was generally detrimental to collaborations. Interviewee C8 summarised a widely held attitude held by ten interviewees that transactional leadership is inappropriate for experimental collaborations.

> *"All of the experiments over my life have gotten larger and larger. Transactional leadership doesn't work" (Source: C8)*

However, Interviewee C8 came from an experimental collaboration background so may not have been in a position to comment on the role of transactional leadership style in both experimental collaborations and accelerator construction. Interviewee C6, who specifically compared accelerator construction and experimental collaborations, echoed this theme:

> *"Accelerator building is transactional, much less democratic than experimentation or even accelerator operation" (Source: C6)*

When asked to explain their disagreement with the concept of transactional leadership, very few interviewees were unable to justify their preconceived notions, but returned to their strong statements regarding a preference for democracy and a constant drive toward consensus, especially among the experimental collaborations. This is discussed in more detail in Section 5.2.10 which considers democratic leadership.

5.2.8 - Laissez-faire leadership

Laissez-faire leadership is characterised by the literature as occurring when leaders allow the group to set goals and methods while the leader usually focuses mainly on ensuring adequate resource provision (Bass and Avolio, 1993; Woods, 2004). All of the interviewees initially perceived laissez-faire leadership negatively in general terms. Interviewees C1 and C2 both summarised the attitude held by many interviewees, by defining laissez-faire leadership as follows:

> *"Laissez-faire isn't leadership at all" (Source: C1)*

And:

> *"Laissez-faire means hoping for the problem to fix itself but it might not be a good idea" (Source: C2)*

Interviewee C9 described a personal experience of a perceived need to intervene in the case of a laissez-faire leader:

> *"Laissez-faire is seen occasionally as they won't make decisions and you need strength to be a leader. One manager[47] was good at tough decisions but fell apart with the basic stuff because he lost confidence and allowed the team to decide everything." (Source: C9)*

There was a widespread perception amongst the interviewees that the concept of laissez-faire leadership is an oxymoron with laissez-faire defined as a passive approach to the team while leadership implies active engagement with it. However, Interviewee C13 quote suggested in Section 5.2.8 that some leaders may give the impression to teams that they are laissez-faire because they were externally focussed and working to put the team

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[47] Although the interviewee said manager, this was referring to the individual's title.

case to other levels of the organisation. Such a case included justifying the allocation of additional resources.

Despite the initial dismissal of laissez-faire leadership, during the discussion three interviewees began to moderate their statements. In these subsequent remarks, these interviewees saw a role for laissez-faire leadership: ultimately, Interviewee C6 even categorised himself as usually laissez-faire:

> *"Personally I'm laissez-faire, I get the resources and let people go deal with the issues" (Source: C6)*

This suggests the possibility that a highly motivated team may not require active involvement from the leader. Instead, the interviewees felt that the leader should focus on resource acquisition and allow the team to select the best technical solutions. This was a concept endorsed in a small percentage of cases as explained by Interviewee C4:

> *"Laissez-faire depends on the group makeup, might be useful in about five to ten percent of situations… if you encounter a genius you've got to give them the freedom to flourish." (Source: C4)*

Interviewee C1 saw a utility for laissez-faire leadership but only in specific situations in combination with other kinds of leadership style:

> *"A mix of transactional and laissez-faire could be useful with high tech stuff as by definition you can't know everything" (Source: C1)*

One interviewee suggested that senior leaders should follow a similar policy:

> *"Being a leader in a big laboratory, you have to remember that most work is done by people. The Director-General for example should try not to act. Understand what's going on elsewhere so that when the bucket arrives you can make the decision." (Source: C16)*

These quotes demonstrate that the majority of scientists perceived little value in laissez-faire leadership. However, three interviewees identified themselves as laissez-faire with very competent teams. In these cases, the interviewees would give individuals the freedom to learn for themselves how to accomplish tasks. Their opinions were that granting freedom to teams should extend to the Director-General, who should allow department heads and project leaders to resolve most situations but still understand the internal dynamic so that if there was a deadlock they were in a position to mediate or take action to deal with it.

The interviewees from both the accelerator construction and the experimental collaborations described a close relationship between the leader and the rest of the team. Six interviewees specifically described the genesis of the relationship as a key moment because the leader should seek to build the best team regardless of their own insecurities:

> *"But you have to choose the right people. Build a team with the confidence that they can do the job better than you could." (Source: C14)*

These same six interviewees felt that, once the team is formed, the leader should generally pursue a hands-off strategy and empower the team to take decisions by themselves, as Interviewee C13 best summarised:

> *"Set a direction but don't interfere …let the team run, only making minor adjustments when something becomes a bottleneck." (Source: C13)*

Five interviewees described that they personally placed the team at the centre of the task, with the leader (i.e. themselves) playing a secondary role. The assessment of success or failure would therefore depend on both the result and the path taken to get there. The quotes below illustrate this:

> *"Being a leader depends on the department and role. But ultimately it's about empowering people and show[ing] off the talents of the team." (Source: C12)*

And:

> *""The leader shines in reflected light" – you need to be aware of that fact. I would be nothing without my team." (Source: C2)*

And:

> *"The result doesn't totally count, but it does very much matter how you arrive there. It's possible to get the right results by a poor means. The*

> *best leaders do well so everyone benefits and it's better if the path matters to the leader." (Source: C9)*

This also demonstrates the attitude considered in Section 5.3.1 that a project provides an opportunity to develop the next generation of researchers. However, seven interviewees acknowledged that while they created a flat structure among their team, the hierarchy does exist and they are ultimately responsible for any issues the team created.

To summarise, although the interviewees reacted negatively to laissez-faire leadership, during further discussion they began to acknowledge that it occasionally had a utility during the construction of the LHC. Principally laissez-faire leadership could be a useful tool when one was presented with obvious genius and for freeing up the leader to focus on other activities elsewhere. In the case of genius, laissez-faire leadership gave them an opportunity to learn for themselves. Many leaders at the LHC also sought to empower their team as the technologies were relatively new. Although the leader was usually the most technically competent in their field, because of the newness of the technology their competence did not always translate. By empowering the team, the leader allowed those working hands-on with the technologies to determine how best to achieve goals while freeing themselves up to work on other activities.

5.2.9 - Authoritarian leadership

Authoritarian leadership offers a contrast to laissez-faire leadership discussed above. While laissez-faire leadership delegates decision-making fully to the group, authoritarian leaders centralise decisions while demanding the group complies with every decision the leader makes (Bass, 1990; Cheng *et al.*, 2004). All of the interviewees viewed authoritarian leadership negatively, with the consensus best summarised by Interviewee C9:

> *"Authoritarianism doesn't work. It gets by for a few years then they don't advance [in terms of career] and they can't see why" (Source: C9)*

One particular individual was repeatedly characterised as representing authoritarian leadership – the first Director-General of the LHC, Carlo Rubbia. Yet despite the negative associations with authoritarian leadership, the scientific community apparently regard Rubbia as a great success (Taubes, 1986; Taubes, 2003). The interviewees were questioned about this disconnect between their dislike of authoritarian leadership and such clear evidence of successful authoritarian leaders both within CERN and elsewhere within science such as the identification by Riordan *et al.* (2015) of Samuel Ting[48] as 'autocratic'. From the four interviewees who commented, Interviewee C15 had a very interesting observation, which summarised the explanations offered:

> *"…they looked past it because he was the guy who could reach the goal. They knew he would deliver" (Source: C15)*

This suggests that authoritarian leadership might have its place within science with the scientific community looking beyond the authoritarianism provided it has faith that the leader will ultimately deliver. However, authoritarian leadership frequently provoked emotional reactions, particularly because of its associations with dictatorships. However, when I suggested that some scientists could be authoritarian leaders, as other authors had described Rubbia and Ting as such (Taubes, 1986; Riordan *et al.* 2015), the interviewees began to open up and described the benefits of authoritarian leadership more readily. Five interviewees who had previously dismissed authoritarian leadership moderated their statements, with Interviewee C11 first to make some concessions:

> *"Authoritarian leadership doesn't work, at least at the department and group level. People need respect and trust… leads to top people leaving. Not giving autonomy doesn't work." (Source: C11)*

However, Interviewee C11 described Carlo Rubbia as both an authoritarian and transformational leader. During the discussion with these interviewees, one interesting finding emerged - the tendency of accelerator physicists to exercise more authoritarian characteristics than experimental collaborators. Interviewee C7 described it in the specific case of Lyn Evans, the project leader of LHC:

> *"Good guy, a bit more authoritarian but that suits accelerator physics, it wouldn't work in experimental collaborations." (Source: C7)*

The quote above also hints at the finding in Section 5.2.10 of the difference in leadership characteristics between accelerator construction and experimental collaboration

[48]Samuel Ting is an American particle physicist who has led several experimental collaborations. His achievements include playing a key role in the discovery of the J/ψ meson particle, which led to his shared award of the 1976 Nobel Prize in physics. Currently he is the principal investigator for the Alpha Magnetic Spectrometer, a particle detector attached to the International Space Station (ISS).

communities, broadly based on the differing financial arrangements. To reiterate these findings, accelerator constructors had centralised control over resources whereas in the experiments, the collaborators controlled resources and senior leaders had to convince others to relinquish them. This shows that, despite the overall negative attitude toward authoritarian leadership, some interviewees perceived benefits of authoritarian leadership. This was more beneficial in accelerator construction because of these structural differences. However, experimental collaborations could relinquish their traditional autonomy in exceptional circumstances such as in a crisis. Nevertheless, the interviewees considered this to be a risky prospect that could give rise to an exodus of talent through the creation of an environment lacking respect and trust, with trust being noted in Section 5.2.3 as an important characteristic of leaders during the construction of the LHC. While some leaders in megascience projects can be very authoritarian, I regard such leaders as relative anomalies rather than representative of *all* leaders in megascience projects.

5.2.10 - Democratic leadership

As the literature examined in Section 2.2.5 explains, democratic leaders set a general strategy and allow followers sufficient autonomy to determine the best method to achieve the goals, while reserving the right to intervene as necessary (Bass, 1990; Gastil, 1994; Wood, 2007). All interviewees viewed democratic leadership favourably, as they did with transformational leadership, especially when teams were working on specific problem-focussed tasks. Four of the interviewees attributed it to the atmosphere of science with highly intelligent trustworthy individuals working together, as exemplified by Interviewee C11:

> *"Democratic leadership is great. A bit of laissez-faire is possible because you can trust these people. CERN isn't full of professional managers so there isn't a 'by the book' way of doing things… People need respect and trust." (Source: C11)*

Interviewee C11's comment that CERN has few professional managers shows the belief that management is about following standardised procedures whereas leadership is about encouraging and assisting teams toward achieving goals. All interviewees from the experimental collaborations deemed democratic leadership to be the single most important leadership style. The interviewees from accelerator construction frequently described how the experimental collaborations had a very different funding situation compared to the LHC construction. All interviewees made this observation, but Interviewees C13, C14, and C15 articulated the most salient differences:

> *"LHC is run by CERN with a normal hierarchy; CERN controls the resources in an 80:20 split with 20% held externally. CMS [One of the experiments] is principally externally funded with 20% CERN resources and 80% held externally. It leads to an experimental spokesperson who's the boss but not really. It leads to a very different style, a much more convincing style trying to always reach a democratic consensus." (Source: C13)*

And:

> *"Most money is central with LHC. All of the parts must work otherwise LHC won't work; if it works without that part then why is it there? With ATLAS [one of the experiments] no money is held centrally and bits can work not quite up to scratch and the machine will still work" (Source: C14)*

And:

> *"ATLAS knows the minimum [technical] requirements but will innovate until the last minute. LHC is similar to space science – lots of effort goes into the design, then it's handed over to industry to fabricate" (Source: C15)*

These quotes demonstrate that leaders in the LHC construction had centralised control of resources so they could send them 'downstream'. This allowed the LHC project to be managed traditionally and those leaders to be more authoritarian. However, in the experimental collaborations, the reverse was true - the experimental collaborators hold the resources and the leaders must convince these collaborators to give them the resources. This necessitates a more consultative and democratic leadership style – rather than being altruistic, this was a reflection of financial realities. The quotes above also illustrate the technical differences between the LHC and its experiments. The LHC was a 'lean' machine in which all parts must work perfectly for it to operate. This is in contrast to the experimental detectors where some machine sub-systems could be underperforming but the entire detector could still work without them. The final point made was that the experimenters primarily designed and built their own equipment while LHC tapped into the economies of scale that industrial fabrication offered, with testing and final assembly taking place on-site.

Therefore, the democratic ideal in experimental collaborations was not just altruistic but also a reflection of financial realities. Interviewees C12 and C15 described the difficulties that experimental collaboration leaders could experience:

> *"It's much harder to be a spokesperson as everything has to be by consensus. It's less efficient* but *you can't do it any other way. It can be very hard to align all vectors rather than have scalar effort." (Source: C12)*

And:

> *"…you've got to understand exactly what* and how *you're going to do, convince and get consensus." (Source: C15)*

Among the experimental collaborations 'consensus' was frequently mentioned: this takes the perspective that most individuals making a decision have the best interests of science at heart. The quote from Interviewee C8 below illustrates this mind-set:

> *"Decisions by consensus on the basis of what is best for science" (Source: C8)*

During these debates over competing technologies, the interviewees felt that scientists *should* be rational and the 'correct' decision *should* be self-evident. There was a definite preference for democratic leadership within an experimental collaboration based on this logic. According to all interviewees, from the collaborations the leader acts as a facilitator of discussion and takes an active role to ensure that scientists are working together, as Interviewee C9 described:

> *"Different [organisational] cultures won't collaborate as they'll take the path of least resistance so an active involvement will be necessary. Democratic leadership is most applicable as you must listen, work together, provide guidance and in my experience, it works best. Allow*

people to work and be the oil that keeps things running smoothly." (Source: C9)

Interviewee C14 strikingly compared his perception of the American 'shootout' model of decision-making to the CERN style of driving toward a consensus, although a consensus is not possible in all cases:

> *"The European way is to look at the technical choices and then argue into a consensus whereas in the US you have a shootout with half the people in the room dead at the end of it. If you talk and explain, the consultation will breed consensus. But you can't build the LHC by consensus" (Source: C14)*

This difference could be an artefact from how the two continents developed their major research laboratories. While American laboratories tend to have founding myths strongly associated with the 'great man' theory of leadership, CERN's founding myth heavily relies on the original CERN council of 'founding fathers'. However, the interviewees did not consider democratic consensus flawless. Interviewee C15 described a specific circumstance of democracy failing to produce a harmonious outcome, which required an intervention from a strong leader:

> *"The main issues were with democracy going too far. We had two potential solutions and the losing one [team] didn't back off. A strong leader had to intervene and say 'no'. It was a waste of time and money… Group consensus or they'll do whatever they want" (Source: C15)*

Two interviewees introduced the idea of guided democracy as a means of solving this issue of democracy going too far. Interviewee C8, who I quoted above as saying that consensus is the only fair way to make decisions, appeared to suggest that such a guided democracy could bring about consensus:

> *"Transformational with democratic leadership works but it needs a guided democracy. Technical decisions can't be a vote – it either works or it doesn't. But if one can get a consensus, then a vote isn't needed." (Source: C8)*

And:

> *"Sometimes it's useful to give the impression of democracy, but a guided democracy like Singapore." (Source: C4)*

This indicates that, despite the democratic ideal amongst the workforce in the two megascience projects, democracy had its limits. This was also apparent in the experimental collaborations where leaders could take steps to guide teams toward what they deemed a 'rational' conclusion. In this case, a leader could exploit their technical competence and reputation to influence a decision; this would be appropriate, for example, when the two competing technologies may require the decision to account for how one technology would interface with others elsewhere. Most teams may focus on selecting the highest specification technologies, but this might not account for how it would work in conjunction with other systems.

5.2.11 - Summary of the characteristics of leaders during the LHC

To summarise the answer the first research question, there are multiple characteristics of leaders in the LHC and its associated experimental collaborations. These include technical competence, management ability, charisma, a vision, respect for the team, and the ability for individuals to exploit some of the style and rhetoric of democracy while actually taking steps to control decision-making. These characteristics varied according to where in the organisation the leader was working and whether the leader was in accelerator construction or an experimental collaboration (See Table 5):

Characteristic	Restrictions
Technical competence	Essential at all levels, but senior leaders often demonstrate this through having prestigious scientific awards
Management ability	Useful at all levels but essential for middle managers
Trustworthiness	Essential for all leaders
Selflessness	Essential for all leaders
Vision	Essential for first senior leader, less important for subsequent senior leaders. Redundant for leaders elsewhere
Charisma	Essential for all leaders
Transactional characteristics (Keeping to budgets and schedules)	Important for middle managers towards the end stages of a project.
Team empowerment	Important for all leaders
Guided democracy	Useful for experimental leaders to create the impression of democracy while exerting significant influence on decisions

Table 5: A summary of the characteristics of leaders of the LHC and associated experiments and which organisational levels the characteristics were observed

5.3 - Where and how were their leadership skills developed?

This section seeks to answer the second and third research questions in the specific case of the LHC:

2. Where were their leadership skills developed?
3. How were their leadership skills developed?

The methods and the situations used for leadership development are often interrelated, so considering them together in the same section is helpful. Many of the interviewees had gone through the CERN leadership development process and had nominated future leaders for training so they were in a good position to comment on the evolution of the mechanics of CERN leadership development.

5.3.1 - Cultural factors affecting leadership development at CERN

As discussed in Section 3.2.2, culture has been cited as a key factor governing the internal performance of an organisation (Robbins and Judge, 2010). Culture acts to create a generally homogeneous workforce and influence decisions regarding the cultivation of leadership. At CERN, there is an attitude that leaders should take an active role in the identification and development of leadership. The experimental collaborations demonstrate an attitude where the development of the next generation of researchers is a key aim. Interviewee C5 described this in the case of the CMS collaboration:

> *"We have to couple experimental success with creating the new generation to take over from us. Our ideal is a community of scientists with the young playing a real role in all parts of the collaboration" (Source: C5)*

This indicates that the development of future researchers and leaders is considered almost as important as making new discoveries. An additional cultural factor is that the interviewees felt that a lack of desire to lead was a substantial obstacle to becoming an effective leader. A leader without the desire would focus on other matters rather than on being a leader. Seven interviewees described desire to lead as an important component of leadership in the CERN context. Interviewee C4, a former group and project leader, best illustrated this attitude:

> *"You need the desire to be a leader. But desire isn't enough. Some need persuading while others need dissuading. People are often chosen but why some and not others? Sometimes it's having no other option for advancement, others because they don't know how to say no, others still blame an over-intrusive HR [Promoting people based on years of service rather than abilities] but I don't think HR is respected enough here." (Source: Interviewee C4)*

This quote demonstrates the perception that the desire to be a leader is one important criterion when determining who should become a leader at CERN. However, there are instances where some people become leaders reluctantly, with such situations blamed on a lack of candidates. Discovering specific examples of reluctant leaders became an important topic during other interviews. The two interviewees who commented presented it to me as a risk that individuals could mark themselves out for career advancement with their technical competence, but this career advancement would take them away from the technology, as Interviewees C7 and C3 stated:

> *"One important issue in high energy physics is that people don't like to step away from their workbench. These are technically good guys but they can't look ahead, it has to be viewed as a partial sacrifice for the overall effort" (Source: C7)*

And:

> *"The main question is 'Do they want it [leadership]?' You have to have that desire. Some want to stick to technical work [rather than move to leadership positions]." (Source: C3)*

These quotes indicate that, although the scientists at CERN are undoubtedly technically competent, some have problems stepping away from 'the workbench' and taking an overview of the entire effort, in other words, taking a leadership role. This issue first became apparent at the first 'rung' of the CERN ladder, the section leader level. CERN has devised proactive solutions to resolve this and prevent these issues emerging at to higher rungs by instituting a formal training programme at this section leader stage. The intention is to remedy these challenges at the earliest stage so it does not occur at higher levels.

The third cultural factor is the very healthy relationship between CERN scientists and non-scientists, which has created a singular focus to work together in all endeavours. One might expect there to be some sort of division between these two communities, but this is not the case as the quote from Interviewee C13 indicates:

> *"We are all completely inspired to further scientific frontiers and it spreads through all grades. That CERN is so focussed is a key strength." (Source: C13)*

This united focus amongst both scientific and administrative staff offered the opportunity for both parties to work together to train the next generation of leaders. As I discuss below in Section 5.3.2, this means that leadership development at CERN allowed both the scientific and administrative groups to devise interrelated leadership training schemes.

5.3.2 - Leadership development at CERN

The LHC project structure, which was mostly separate from the core organisation, had no responsibility for the training programmes as leadership development was outside the project scope. This was due to the lack of available project resources in turn due to the economic and political climate during the approval phase of the LHC described in Appendix 1. Instead, the rest of the CERN organisational structure assumed responsibility for leadership identification and development. The group leaders would primarily search for individuals with leadership potential and cultivate them. Two tracks exist, one technically-focussed and one more managerial, with the option to bypass some stages rather than taking the 'traditional' progression route from group leader to section leader to department leader. Interviewee C12 described his own experiences of promotion within CERN:

> *"CERN is very much like a civil service but it does have multiple career tracks, one leadership directed, and one technical directed. I advanced very quickly and bypassed the normal process. I was never a Group Leader." (Source: C12)*

The technically-directed pathway offers an alternative promotion route without creating reluctant managers or losing their technical skills. In the case of the leadership pathway, the central laboratory ran training programmes with the motivation described by Interviewee C3:

> *"…implemented training for future leaders to give them a survival kit. We taught them how CERN works and it's been very successful. It's given when they become a Section Leader." (Source: C3)*

These programmes sought to engage with individuals early in their career: training was given when they reached the first 'rung' on the CERN ladder, the section leader level, to give them useful skills and help them understand how CERN functions as an organisation. They provide a new section leader with an overview of how to manage teams, how to interface with the rest of the organisation, and other necessary day-to-day management tools. This second aspect of the training ensured that teams did not suffer while their new section leader learnt about the organisation of CERN. The laboratory and the collaborations generally used similar processes for the selection of leaders, especially at the problem-focussed levels. This took the form of a vote, as described by Interviewee C15 in the case of the ATLAS collaboration:

> *"...it's an elected position although there's a selection committee for two years and a higher majority is required for subsequent terms." (Source: C15)*

Although the requirement for larger majorities for renewed leadership terms is an organisational quirk within ATLAS, it nonetheless demonstrates an attitude shared by both experimental collaborations and accelerator constructors. This is that a team grants leadership to an individual either informally based on their technical competence, or through a formal vote. This is apparent at most levels within CERN, the LHC project, and the experimental collaborations. The voting mechanism is particularly popular in the experimental collaborations as a tool to select the senior leader of the collaboration, termed the 'spokesperson'.

This is not the case for all senior leaders; the CERN Council appoints project leaders, department heads, and Directors-General. The appointment of a project leader or department head is slightly different to the selection of a Director-General, but the Council still acts to confirm the Director-General's nominee. Interviewee C14 described the previous process for the nomination of the Director-General:

> *"How the DG [the acronym for Director-General] was chosen was different from now; back then the SPC [Scientific Policy Committee] issued recommendations based on their scientific and management ability and also their suitability for the long-term plan" (Source: C14)*

This further underlines my findings from Sections 5.2.1 and 5.2.2 that technical competence and management ability are important assets for a Director-General and a project leader. It also indicates that the SPC sought to tailor the selection based on the needs of the 'plan', which includes the needs of the LHC. A number of archival documents described the new procedures for selecting a Director-General. These reduced the role of the SPC in the process and required the Council to appoint a candidate only after a candidate had secured a minimum two-thirds majority. The qualification profile used during the 2011 Director-General search gave primacy to the following qualities:

> *"- outstanding expertise and a high reputation in particle physics and/or closely related fields;*
>
> *- capacity for providing scientific and managerial leadership for CERN, for representing the Organization in dealings with governments and other bodies in and outside the Member States and for effective building of consensus within the Organization, the Member States and internationally." (Source: CERN/2329/REV.2)*

This indicates that technical competence and management ability have retained their importance despite these changes in procedure. It also shows that a Director-General must display these characteristics in order to build consensus with a wide variety of stakeholders. 'Consensus' is an important concept, because it underpins democratic leadership in the experimental collaborations, as discussed in Section 5.2.10. Although the training procedures for new Directors-General were not described in the archival material or by the interviewees, the press release announcing a new Director-General included a 'transition year' in which the Director-General designate would work closely with the current Director-General (Personnel, 2008; O'Luanaigh, 2014). This transition year is an opportunity for the current Director-General to mentor the next one, introduce them to important stakeholders, and helping them to understand the nature of the role.

5.4 - Tailoring the selection of different leaders for specific phases of the project

One important theme that emerged during the fieldwork was that the selection of each Director-General was heavily influenced by the phase of the project. This, as discussed in the Tevatron case study, was also observed. About half of the interviewees said that the tradition that a CERN Director-General served a single five-year term offered an opportunity to select the Director-General to suit the specific needs of the project at that time, as suggested by Interviewees C1, C15, and C16:

> *"There were four DGs [Directors General] over the life of LHC, all very suited to the period [of time] and part of the project" (Source: C1)*

And:

> *"You need transformational leadership at some point in the project lifecycle, a [Robert] Wilson-esque person [the first director of*

> *Fermilab]. The vision to do something great. At other times, it's useless. The R&D phase requires a different leader and you become more transactional or democratic toward the end stages." (Source: C15)*

And:

> *"The definition of success varies between leaders. Carlo Rubbia had to launch and defend the LHC - he was credible and people followed him. Christopher Llewellyn-Smith was very capable of organising the discussion… Maiani had to weather the storm of closing LEP for LHC, prove the 700MCHF was necessary and keep faith that we would find the Higgs before Fermilab" (Source: C16)*

The concept that Directors-General had differing goals to fulfil during their tenures was one that first emerged during the fieldwork at Fermilab, with Interviewee F7 observing:

> *"At CERN the LHC effectively ran the lab. Each DG was selected to suit the needs of the project, building then upgrading; [I] bet that there'll be a data miner next." (Source: F7)*

As Interviewee F7 made this comment early in 2014 when the interview was conducted, it is possible to judge whether this interviewee's hypothesis is correct. The current Director-General was selected at the end of 2014, with a year spent as an 'apprentice' before formally commencing their tenure. She is Fabiola Gianotti, who was the ATLAS spokesperson during the crucial data analysis ahead of the Higgs boson announcement (O'Luanaigh, 2014). As Interviewee F7 predicted a 'data miner' and Gianotti served during this crucial period, this might be seen as an astute observation. Furthermore, currently CERN has focussed on fully exploiting LHC by increasing data production rates while also allocating resources to the HL-LHC (High Luminosity LHC – see footnote 45) briefly described in Section 5.2.6.1. This gives additional credibility to the claim of Interviewee F7 that while CERN is focussing on its current activities, it is also thinking about the next major advance. In this case study, I primarily focus on the characteristics of the Directors-General as individual leaders. I consider the issue in more generalised terms in Section 6.4, which draws together similar findings from both Fermilab and CERN on this topic.

5.4.1 - Carlo Rubbia

Carlo Rubbia served as Director-General in the early years of the LHC and during this period, he nurtured the LHC with personal involvement in many of the discussions. These included defending the LHC from questions by policy-makers concerning its value when the proposed SSC would be a 'superior' machine (Smith, 2007). Approximately three quarters of the interviewees had personal experiences of Rubbia while the remaining quarter knew him by reputation. All comments featured two obvious themes about Rubbia. The first was his brilliance as a physicist, with five interviewees describing him as 'brilliant' or as a 'genius'. Evidently they had either overlooked or were not concerned that on at least one occasion Rubbia had made claims of new discoveries that later had to be retracted (Taubes, 1986). However, all interviewees agreed that working with Rubbia could be a challenge. Interviewees C1 and C11 best described what many other interviewees had implied in describing Rubbia's leadership in the following terms:

> *"As far from real management as you could possibly get. Everyone loved him, but he was hell to work with. Charismatic. Unpredictable. Carlo Rubbia could destroy you if you weren't of strong character. He almost alienated people but still putting out wacky ideas even now!" (Source: C1)*

And:

> *"…an infamous authoritarian leader. Doesn't suffer fools gladly but transformational, without a doubt" (Source: C11)*

Two interviewees even suggested that, despite his ability to marshal resources to ensure success as described by Krige (2001), he dominated CERN to such the extent that the entire organisation became dependent on him:

> *"I knew his reputation but the meeting of the directorate was incredible as they were like mice around him." (Source: C4)*

And:

> *"You could never grow a leader like him using a textbook… [but] I could see the culture of fear he left" (Source: C2)*

This situation, described by Interviewee C2 as a ‘culture of fear’, strengthens the observation in Section 5.2.9 that authoritarian leaders can drive out talent. It further suggests that leaders of an organisation should not seek to master all of its resources. Such an approach could lead to an entire organisation becoming dependent on a single individual, creating a power vacuum at the end of their tenure. However, three quarters of the interviewees reported that he was uniquely qualified to defend the LHC from attacks regarding its scientific merit in the 1980s and 1990s, as described by Interviewee C16:

> *“Carlo Rubbia was doing LEP but left room for the hadron collider. The DG can’t be a manager but has to follow science, the scientists wanted a neutrino beam, but Carlo knew that a large hadron collider had the science… [you] can’t be revolutionary with an institution - you have to be more cautious but you can’t just follow public opinion.” (Source: C16)*

Rubbia is still producing new ideas for future accelerators, with two interviewees describing specific instances of recent contact in which Rubbia proposed new experimental ideas but was not able to complete them, as the quotes below indicate:

> *“[Rubbia]… could have achieved more if he mastered himself. He had this tendency to flit between projects. I thought it was his way, seeking leadership to escape his present” (Source: C6)*

And:

> *“One Christmas Eve I was about to leave at 7PM, when I suddenly get this four-page proposal for another experiment [From Rubbia]. A brilliant mind, got results but not able to produce a community or the next generation” (Source: C5)*

These quotes demonstrate Rubbia’s ability to propose new experiments and shepherd the concept through the early stages. However, Interviewee C6’s quote suggests that he had a tendency to lose interest in any single one. This indicates a similarity between Rubbia and Robert Wilson, considered in Section 4.4. In both cases, the interviewees at their respective laboratories considered them excellent project initiators but less adept at the completion of projects. This is explored in detail in Section 6.4.

Regarding Rubbia's characteristics as a leader, there was no doubt that he was clearly technically competent. The quotes from the interviewees above demonstrate that he is one of the best scientific minds of his generation. He was a transformational leader but very authoritarian. As Krige (2001) noted, he was able to execute a successful experiment that changed the balance of power between the United States and Europe, so his authoritarian style did not prove detrimental to his career. This is a relative anomaly amongst the normally democratic experimental collaborators, but the community looked past this because they knew he could deliver. However, I would argue that Rubbia did not have particularly strong managerial ability. He was a transformational leader who created visions but did not necessarily strive to see them through to completion. I have discovered other designs he has proposed to solve several challenges such as a sub-critical nuclear reactor, a proposed reactor that avoids many of the issues associated with conventional nuclear power generation (Rubbia, 1994). These further demonstrate his ability to devise technologically viable visions.

However, it is difficult to determine how Rubbia was trained as a leader. Rubbia received his doctorate in Italy and almost immediately moved to the United States for a postdoc, dividing his time between there and CERN. I agree with Interviewee C2's assessment that, because of his unusual characteristics within the experimental community, Rubbia probably received no formal leadership training. As I observed in the Fermilab case study in Chapter 4, during the period where Rubbia was living in the United States, the American scientific community did not regard leadership training programmes as being particularly useful. It is therefore reasonable to assume that Rubbia did not receive any such instruction, but instead gained extensive experience through his many scientific experiments and through learning from earlier mistakes and failures.

5.4.2 - Christopher Llewellyn-Smith

Christopher Llewellyn-Smith was the second Director-General over the LHC period. During his tenure, the CERN Council formally approved the LHC as a two-stage project and, through various creative funding mechanisms devised by CERN management, later upgraded this to a single-stage project. Securing the future of the LHC became more challenging as national governments were cutting budgets at that time in an environment of changing priorities (Fraser, 1997; Smith, 2007; Evans, 2009).

All of the interviewees spoke about Llewellyn-Smith almost wholly in positive terms. Interviewee C1 put forward a view held by all interviewees who were at CERN during the Director-General transition that highlights the contrast in leadership styles between Rubbia and the new Llewellyn-Smith:

> *"Carlo Rubbia was more confrontational but when Christopher Llewellyn-Smith came in, the doors just opened for this polite English gentleman." (Source: C1)*

The interviewees felt that this leadership change enabled CERN management to achieve its main goal, of securing the funding needed to build the LHC, as Interviewee C1 again best described:

> *"Christopher Llewellyn-Smith was a great guy. Only here for five years, but he came in as great scientist and diplomat. Got LHC approved and got contributions from non-Member States. His management style is to like structure." (Source: C1)*

The statement from Interviewee C1 that Llewellyn-Smith liked 'structure' indicates that, during this time, CERN operated with more clearly defined roles of responsibility and operating procedures than before. These roles and procedures allowed the delegation of tasks while making it easier to understand which individual was responsible for a given task. During Llewellyn-Smith's tenure as Director-General, CERN was developing diplomatic agreements to turn Rubbia's vision of the LHC into a workable plan. It was not possible for Llewellyn-Smith, nor was it in his character, to dominate all of these processes. Instead, he had to delegate to others and manage these threads of negotiation. This provides a contrast with Rubbia, who took a more direct role in all such matters. Llewellyn-Smith's tendency to create structures represented a more transactional leadership style, but also reflected the many activities required to set the LHC on the way construction. However, not all of the interviewees approved of his more transactional style. One interviewee echoed the view held by two other interviewees when he described Llewellyn-Smith as:

> *"Christopher Llewellyn-Smith was more transactional. Aloof to be honest. Oxford don style. He was often off fighting big battles away*

> *from the lab and would come into the control room like royalty." (Source: C11)*

The interviewees did not share the same opinion regarding the leadership category that Llewellyn-Smith occupied as Director-General. There was a wide spread of categorisations, with most interviewees describing Llewellyn-Smith as adopting a combination of styles. From these varying combinations, the most popular were transformational and democratic, although two interviewees also categorised Llewellyn-Smith to a lesser extent as transactional. The introduction of more transactional leadership bolsters the argument made in Section 5.2.7 that leaders become more transactional as the project progresses. In this case, a new leader with the desired behaviours is selected rather than, as the literature suggests, the leader adopting the necessary new behaviours (Bass, 1990). When asked about Llewellyn-Smith's purpose in relation to the LHC, almost all interviewees stated that his success was in taking Rubbia's vision and turning it into something that was realistically achievable, as described by Interviewee C6:

> *"… A great DG for getting LHC approved. Required a lot of deal making, he was definitely the right person at the right time." (Source: C6)*

Effectively the change was from *which* accelerator to *how* to build the chosen accelerator, with the vision changing to become viable. Llewellyn-Smith developed a series of novel diplomatic agreements to obtain the necessary approval and funding, as this quote from Interviewee C16 indicates:

> *"[Llewellyn-Smith] managed to get the US on board, and Japan which was harder, and Russia, which was very easy. He had the vision and made the barriers move." (Source: C16)*

The first key diplomatic move made by Llewellyn-Smith appears on the surface to have been a compromise agreement, described by the literature as the 'missing magnet machine' (Fraser, 1997; Smith, 2007; Evans, 2009). The original LHC proposal submitted to the CERN Council called for the LHC to be a two-stage programme. In the first stage, only two thirds of the magnets would be installed and the first experimental run would have taken place at 7TeV. A second stage would install the remaining magnets and allow beam collisions at the full design energy. Even though the final budget would have been larger than a single-stage project, a reduction in annual contributions was more palatable to member states. As a result of displaying a willingness to work within the concerns of member states, the Council approved LHC as a two-stage programme in December 1994 (Fraser, 1997; Smith, 2007). There was also an understanding that the decision would be revisited should CERN management secure additional funding. Certainly, the literature has debated whether this missing magnet machine would have ever operated or was merely pursued as a means of 'focussing minds', as Interviewee C16 hinted (Fraser, 1997; Evans, 2009):

> *"The 'Missing Magnet Machine' was a good move; it definitely helped to build support and probably made it possible to get money from the US to build the machine" (Source: C16)*

Regardless, this demonstrates the ability of Llewellyn-Smith to obtain diplomatic agreement even in a difficult environment. A second key diplomatic agreement developed by Llewellyn-Smith was the negotiation of 'special host-state contributions'. This was intended to solve a longstanding issue. Other member states felt that the CERN host-states, namely France and Switzerland, benefitted from having the laboratory located on their territory. However, their contributions to the CERN budget did not reflect these benefits. During the negotiations to approve LHC, some member states voiced concerns that the host state question had still not been resolved. In an environment of reduced contributions to CERN, Llewellyn-Smith managed to negotiate additional contributions from the host states. From these negotiations came the agreement that the host states would effectively maintain their budget contributions in real terms while the other member states saw reductions in their contributions .

The third key diplomatic agreement that Llewellyn-Smith negotiated was to obtain contributions from non-member states. This resulted in the extension of a rarely used category of CERN membership, observer status, in order to secure these contributions. Historically, observer status was used for countries that were not yet deemed appropriate candidates for full membership (Hermann *et al.*, 1987b; Hermann *et al.*, 1987a). However, after the cancellation of the Superconducting Super Collider[49] in the USA, both the American and Japanese particle physics communities had no realistic alternative to the LHC (Riordan *et al.*, 2015). This presented an opportunity to exchange access for budget contributions. The extension of CERN observer status to several countries,

[49] I discuss the Superconducting Super Collider in detail in Appendix 1.

notably the USA, Japan, and Russia, allowed CERN to bridge the budgetary gap between the first stage of the ‘missing magnet machine’ and a single-stage project.

Approaching the first research question to identify Llewellyn-Smith’s characteristics requires a distinction over the definition of technical competence. Llewellyn-Smith was neither directly involved in accelerator construction nor experimental collaborations. His background was in theoretical physics, where the definition of being technically competence does not necessarily require hands-on contact with the technology, as described by Interviewee C6:

> *“In theory [the shortened term for the CERN theoretical physics department] it’s different from experiments or accelerator physics. The skills may vary but idea generation is key. Then it’s having good ideas, working out ideas, explaining ideas, and being able to share those ideas with the young especially…[Llewellyn-Smith] had obstacles with short inspirational ability. He was very self-contained and focussed on [the] job at hand, not charisma. It worked well in particle physics but not more political roles.” (Source: C6)*

As this quote and others in this section elucidate, the real strengths of Llewellyn-Smith lay in taking Rubbia’s vision for the LHC and turning it into a workable plan. However, apart from than the customary transition year before he became Director-General, Llewellyn-Smith received no formal leadership training. Instead, he became familiar with CERN by becoming an adviser to major inquiries. The first was the Kendrew report, commissioned by the British government to assess the returns from its contribution to CERN (Mulvey, 1985; Fraser, 1997). Although the report praised CERN for its science, it recommended that the British government seek a 25% reduction in CERN expenditure (Mulvey, 1985). If this reduction was not forthcoming, then the report recommended UK should leave CERN (Mulvey, 1985; Fraser, 1997). After this inquiry, Llewellyn-Smith moved to CERN as member of the Scientific Policy Committee (SPC). The second report with which that Llewellyn-Smith assisted was the Abragam report, a CERN inquiry commissioned in response to the Kendrew report, to determine how to make the savings necessary to keep the UK in CERN (Fagan, 1987). These experiences served to develop his management abilities with a specific emphasis on CERN. Llewellyn-Smith’s training for CERN was almost entirely acquired from experience in serving as an adviser to scientific enquiries and from being a member of the CERN Scientific Policy Committee. These experiences gave him a deep understanding of the strengths and weaknesses of CERN. This would have served him well when trying to secure the funding for the LHC, even as member states sought to cut their contributions.

5.4.3 - Luciano Maiani

Luciano Maiani was the third Director-General during the lifetime of the LHC. During his tenure, the majority of the LHC's construction took place. About three quarters of the interviewees described the laboratory atmosphere during this time as being focussed solely on LHC. The role of CERN management was to track the project and maintain the confidence of the Council in the project. Only a single interviewee described Maiani specifically, probably because by that stage the LHC project leader was mostly running the project and Maiani's task was primarily to provide oversight; this interviewee categorised him in relation to the other Directors-General:

> *"We had Christopher Llewellyn-Smith and Carlo Rubbia in the late 80s and 90s, what about after that? Luciano Maiani was less organised, less democratic, more authoritarian. He didn't discuss so much." (Source: C6)*

This may not be a surprising assessment, considering that the laboratory was then focussed on building the LHC, with the majority of the technological principles understood at that point. The project could be managed in a more traditional manner, focussing on cost-control and remaining on schedule. Unfortunately, during 2001, a re-calibration of the budget to account for changes in the wider economic environment revealed that the projected costings from the 1990s were very optimistic and there was now a budget gap of around 700MCHF, triggering a budgetary crisis (Adam, 2001). Obviously, the CERN Council would have concerns that the LHC was risking a large cost overrun, as the SSC had recently done (Riordan *et al.*, 2015). Therefore, regaining the trust of the CERN Council was paramount in the eyes of CERN management. Over the next six months, CERN management determined what percentage of this shortfall could be recouped from the laboratory budget. At the end of the review, management offered the CERN Council a deal, in which CERN would fund 300MCHF of the shortfall, but the remaining budget gap would require funding from the member states. Interviewee C16 summarised the situation at CERN during this time:

> *"In September 2001 a new costing assessment came in with an extra cost of 20% and other costs exposed. Infrastructure upgrades hadn't been accounted for originally but were now being incorporated into the budget, around 700MCHF extra. 200MCHF in costings, 500MCHF in infrastructure. We had discussions about how to handle this with member states. CERN agreed to make savings to the effect of 300MCHF and share the remaining with Member States… We managed to eke out the budget over more time but regardless we had to close down every machine for a year to make the savings" (Source: C16)*

Widespread changes were introduced in exchange for the additional 400MCHF from Member States to reassure the CERN Council that LHC spending was under control. This included introducing a new accounting method discussed earlier in Section 5.2.2, Earned Value Management. Interestingly the project leader was not replaced, an unusual course of action as there is evidence from other non-scientific large projects of project leaders being replaced as a result of a budget crisis (Anderson and Roskrow, 2003).

Maiani's characteristics as a leader were rather similar to those of Llewellyn-Smith considered above in Section 5.4.2. Both were more transactional than Rubbia, but while Llewellyn-Smith was democratic, Maiani's tenure marked a return to a somewhat more authoritarian style of leadership at CERN. However, none of the interviewees described Maiani as being as authoritarian as Rubbia, contrasting the more benevolent authoritarian style of Maiani with that of Rubbia's (Likert, 1977). As Llewellyn-Smith had secured the funding to enable the construction of the LHC, Maiani's primary role was to provide management oversight on behalf of the CERN Council. When there were issues, such as the 2001 budget crisis, he intervened to maintain the trust of the Council and demonstrate that the LHC project was under control. In this sense, he had similar diplomatic abilities to Llewellyn-Smith but they were aimed at different goals.

In terms of identifying Maiani's leadership training, as I noted above, both he and Llewellyn-Smith were from the world of theoretical physics. Furthermore, they both came to CERN through the Scientific Policy Committee route. However, Maiani then became an Italian delegate to the CERN Council and subsequently President of the Council, whereas Llewellyn-Smith moved directly from the Scientific Policy Committee to the position of Director-General (CERN, 1996; Fraser, 1997; Smith, 2007). Again, aside from the traditional transition year where the Director-General and Director-General-designate work together to ensure an orderly transition, I could not identify any formal leadership training received by Maiani.

5.4.4 - Robert Aymar

Robert Aymar was the fourth and final Director-General during the construction of the LHC, moving from President of the CERN Council where he served during Maiani's tenure. During that earlier period, he oversaw actions during the 2001 budget crisis. Therefore, Aymar was an important person to convince that the measures taken by CERN management were reasonable and sustainable. Throughout this period, a key concern of the Council would have been the protection of member states from a cost overrun similar to that which had triggered the recent cancellation of the SSC (Riordan *et al.*, 2015). During his time as Director-General the LHC was completed but unfortunately the 2008 magnet, quench incident also took place, a major incident resulting in damage to the LHC's magnet systems. Aymar was categorised by all the interviewees as being more authoritarian than the other Directors-General and particularly strongly by the five interviewees who were willing to discuss him. Three interviewees even suggested that he was not a 'true' member of the CERN community, as exemplified by Interviewee C6's quote:

> *"Aymar was definitely authoritarian, like a General as he was one. It doesn't work in high energy physics so there was a cultural conflict." (Source: C6)*

This is unsurprising given the quote from Interviewee C6 above, where authoritarianism is viewed positively at the end stages of a project when things should be more technically certain as discussed in Section 5.2.9. However, the magnet quench incident required a level of tolerance of delays and two interviewees alleged that he was:

> *"…essentially a manager by pushing for collisions without tests." (Source: C16)*

The implications of a crisis might have been that the authoritarian leader is forced to suddenly become more tolerant of delays and cost increases. While Interviewee C6's quote comparing him to a General indicates a gulf existed between the CERN community and CERN management during this time, I found no evidence to substantiate Interviewee C6's suggestion that Aymar actually might have held the rank of General. However, upon closer investigation, these descriptions of Aymar do seem to have been based on his background. Aymar spent time in the French *Corps des ingénieurs des poudres et explosifs*, whereas the other Directors-General during the LHC project worked solely on basic science with no military applications or experience.[50] The selection of Aymar probably represented a desire on the part of the CERN Council for continuity of leadership for the final stages of the LHC project. Given his previous roles as the President of the CERN Council and Chair of the 2001 External Review Committee during the budget crisis, Aymar already understood the key issues associated with the LHC. Such an understanding would have helped him to minimise any issues during the transition from Maiani to Aymar and ensured that CERN had competent management during the critical final phases of the LHC project.

Aymar exhibited similar characteristics to Maiani in that he was both transactional and authoritarian. This grated with the CERN community, as illustrated by the comments that Aymar pushed for collisions without tests and that he acted in a manner not dissimilar from a General. While the interviewees did not specifically describe his technical competence, given that the CERN Council wanted a leader who would oversee the LHC start-up, this may not have been a substantial concern. Aymar also chaired the external review committee that investigated the viability of the LHC during the 2001 budget crisis. This indicates that he was fully familiar with the issues associated with the construction of the LHC.

Where Aymar developed his leadership characteristics is also an interesting question. Like most of the Directors-General, Aymar spent little time working at CERN prior to his appointment as Director-General. As I discussed above, Aymar was rather unusual in that a significant part of his research took place in a military laboratory. While I found no records that he actually was promoted to the rank of General, such experience would have most probably affected his leadership characteristics.

[50] An approximate translation for this is Corps of Powders and Explosives Engineers.

5.5 - Summary

In this chapter, I present the findings from the second case study, focussing on the LHC at CERN. In relation to the first research question, namely “What are the characteristics of those who lead megascience projects?”, my findings suggest firstly that technical competence was deemed the most important characteristics of a leader in the LHC. This technical competence was the quality by which leaders gained and maintained respect. Secondly, managerial skills were considered extremely important for leaders during the LHC, as these managerial skills proved essential to keep the project on track. These managerial skills could be used to demonstrate to external stakeholders that the LHC project was under control, thereby maintaining their trust. The interviewees linked the importance of trustworthiness and selflessness. Being worthy of the trust of others meant that a leader trusted their team to complete tasks while selflessness related to keeping a focus on important matters such as the project and away from any personal ego. The interviewees believed that a vision and charisma were important characteristics of leaders but it was not universally necessary. Middle managers could realise any senior leader’s vision, so leaders below the senior leader did not need a separate vision. Despite the interviewees from both accelerator construction and experimental collaborations expressing a strongly negative attitude toward authoritarian leadership in megascience projects, there was agreement that such a leadership style can be highly successful. Such an observation was made of the accelerator construction projects, suggesting that megascience projects are similar to large technical projects in that they do not involve uncertain technological developments. Within the experimental collaborations, there was extreme resistance to this view, with the collaborations preferring a democratic leader to represent the wishes of the community. This implies that the experimental collaborations embody leadership styles more suitable to technically uncertain projects than large ones. However, many of the same interviewees from the collaborations said that democracy often went too far and that a form of ‘guided democracy’ might be more appropriate (see Section 6.2.6 for further discussion).

In relation to the second and third research questions regarding “Where were these leadership skills developed?” and “How were these leadership skills developed?”, the findings from this case study indicate that the majority of leaders are identified by their fellow team members. However, many leaders also take a role in the identification of some leaders, as there is a basic cultural belief that the community has a responsibility to develop the next generation of researchers. The interviewees regarded this development process as being equally important to the making of discoveries. Most individuals who emerge organically as leaders eventually find themselves elected to a more senior role within the laboratory or collaboration. While there are many technically competent leaders, some do not wish to leave their “bench”. In response to this, CERN has developed two pathways. One is for future leaders while the second is a technical pathway. This ensures that those who are extremely technically competent do not have to step away from working hands-on with the technology for career advancement, and thus prevents the loss of valuable tacit knowledge and skills.

The leadership pathway involves a combination of practical experience and training programmes. This practical experience comes in the form of running a small research group but the leader also attends a training programme with a combination of group learning and practical experience. In this case, *where* and *how* leadership is developed at CERN is usually within the laboratory or collaboration context as the leader of a small team using a combination of this practical experience *and* formal training programmes devised by the laboratory.

The final key finding from this case study is the selection of Directors-General each of whom was tailored to enable the five-year goals of the organisation. This too has been found in the Tevatron case study. In the case of CERN, when discussing the Directors-General who served during the period under investigation, the interviewees described how each Director-General was particularly well suited to enabling the part of the LHC project that coincided with their tenure. From their comments, it seems logical that CERN took advantage of the five-year tenure of a Director-General and tailored the selection to the anticipated needs of the LHC project over the next five years. This began with Carlo Rubbia acting as a transformational leader who created a vision that unified the laboratory around a specific accelerator. The next three Directors-General then realised this vision through subsequent tenures. The second Director-General over this period, the more democratic Christopher Llewellyn-Smith, put in place the necessary diplomatic agreements to secure the future of the LHC.

The third and fourth Directors-General, Luciano Maiani and Robert Aymar respectively, were recruited with the intention of getting the LHC constructed on time and on budget. These two Directors-General were rather more transactional and even authoritarian, which proved necessary to keep the LHC under control during its construction. However, they each experienced shocks that challenged them to stick to the timetable. One interesting finding is that among the Directors-General who I investigated, Rubbia is the only one who had extensive experience working within the laboratory as an experimental collaborator. The other Directors-General over this period developed their leadership characteristics through experience working on scientific policy-related matters. I discuss these findings in detail in Chapter 6, and compare them with the findings from the Fermilab case study.

Chapter 6 – Discussion

This chapter discusses the findings from the two case studies in relation to each other and to the literature reviewed in Chapter 2. It aims to answer the research questions in a more general sense by synthesising the findings concerning Fermilab and the LHC in Chapters 4 and 5. To remind the reader again, these research questions are:

1. What are the characteristics of those who lead megascience projects?
2. Where were their leadership skills developed?
3. How were their leadership skills developed?

This chapter is composed of five sections. Section 6.1 comprises a discussion on the application of the conceptual framework originally chosen for this thesis, namely the notion of the 'heterogeneous engineer'. Sections 6.2 and 6.3 discuss the findings in the context of previous literature with particular attention to addressing the research questions first identified in Section 2.6. In Section 6.4, I discuss an unexpected finding which was that the selection of senior leaders was tailored to suit the phase-specific needs of the project. In Section 6.5, I consider alternative theories for my observations to demonstrate the robustness of my analysis, with Section 6.6 summarising the main conclusions of the chapter. For the purposes of identifying leadership characteristics for this thesis, I created a three-level model where I divided the organisation into *senior leadership, middle management, and problem focussed levels*. I chose to create this model in line with the idea from Mumford *et al.* (2007) that skills, and therefore the characteristics of leaders, can vary according to the level of the organisation.

6.1 - The heterogeneous engineer as the conceptual framework

The conceptual framework of the heterogeneous engineer considered in Section 2.7.3 was intended to provide a theoretical framework for understanding leadership in megascience projects (Krige, 2001). To briefly reiterate, the heterogeneous engineer concept is a person-embodied interpretation of Law's (1987a) 'heterogeneous engineering' (Krige, 2001). According to Krige (2001), the heterogeneous engineer seeks to "mobilise the human and material resources needed to attain his objectives". Krige (2001) cited Carlo Rubbia as an exemplar heterogeneous engineer for his key role in the discovery of the W and Z bosons in the 1980s, including taking a central role in many decisions. The description of Rubbia taking direct control over many important issues seems unusual, considering that the interviewees in Section 5.2.10 described democracy and devolved responsibility as the key characteristics of leadership in experimental collaborations.

During the fieldwork, the link between the conceptual framework and the LHC project through Carlo Rubbia offered the opportunity to compare a heterogeneous engineer who had previously been identified to other leaders in megascience projects. This potentially allowed me to use the heterogeneous engineer concept as a framework to develop my theories concerning leadership in megascience projects.

The leadership literature has not previously sought to link the concept of the heterogeneous engineer and the five leadership styles. However, drawing upon the evidence obtained from the two case studies, I observed that both the Tevatron and the LHC originally had highly charismatic and authoritarian leaders to develop a vision for the accelerator and then to unite their laboratories around it. At Fermilab and CERN, these individuals were Robert Wilson and Carlo Rubbia respectively. One interviewee at CERN even identified a 'Wilson-esque' leader as a key type of leader for getting a big project off the ground. As identified in Sections 4.4 and 5.4.1, both Wilson and Rubbia exhibited a combination of authoritarian and transformational leadership characteristics. Equally, the heterogeneous engineer exhibits many of the characteristics associated with a combination of transformational and authoritarian leadership. This is not a surprising combination, given that the literature previously identified that transformational leaders are very good at uniting teams around a vision and authoritarian leaders are effective for centralising decision-making in a single individual and ensuring compliance. Likewise, the vision can act as a means to induce compliance.

However, in terms of using the heterogeneous engineer as a broader basis for leadership theory, I have concluded that Krige (2001) attempted to develop the heterogeneous engineer concept using a relative anomaly as the foundation. As discussed in Section 5.2.10, leadership in experimental collaborations normally manifests itself in a highly democratic fashion. However, both Krige (2001) and Taubes (1986) describe Rubbia in distinctly authoritarian terms, an apparent anomaly within the highly democratic field of experimental collaborations. This is why it has proven such a challenge to incorporate the concept of the heterogeneous engineer into a broader theoretical perspective. Rubbia is not the only leader within science to be classified as authoritarian, one other example being Samuel Ting (See footnote 48), but such individuals are generally considered to be exceptions (Riordan *et al.*, 2015). The heterogeneous engineer concept has certainly been useful during the intellectual journey of this thesis. However, it was not possible to use it as the basis for developing a broader theoretical framework of studying leadership in megascience projects. Instead, I found the five leadership styles considered in Section 2.2 to be more useful for the interpretation of the leadership characteristics observed in Chapters 4 and 5. To reiterate, these five leadership styles are transformational, transactional, laissez-faire, authoritarian, and democratic leadership. These well-established primary leadership styles have proved very relevant to categorising how leadership manifests itself within megascience projects.

In the following two sections, I seek to answer the research questions. Each section briefly restates the research question it seeks to address and summarises the findings from each case study, discussing the similarities and differences between the two case studies. Furthermore, I will draw upon the appropriate literature and aspects of the five leadership styles to establish the relationship of my findings to the literature.

6.2 - What are the characteristics of those who lead megascience projects?

This section seeks to answer the first research question in relation to both the Tevatron and the LHC. Certain key themes emerged repeatedly during the thematic analysis of the data that I obtained from Fermilab and CERN. As will be demonstrated in this section, many of these themes were common to both laboratories, although there were also significant differences. This section will also discuss the attitudes of the interviewees at both Fermilab and CERN in relation to the five leadership styles to uncover additional characteristics of leaders in megascience projects. However, there are differences in the characteristics of leaders which varied according to the level of the organisation. I used the leadership skills strataplex, discussed in Section 2.3.2, to stratify the organisation into three levels, which I described as senior leadership, middle management, and problem-focussed levels (Mumford *et al.*, 2007).

6.2.1 - Technical competence, management ability, and trustworthiness

The interviewees at Fermilab consistently identified technical competence as the most important component of leadership. This technical competence provided a foundation for respect and demonstrated to team members that the leader possesses good technical judgement. One can therefore conclude that a leader without this foundation for respect would struggle to gain or maintain their position. This is in contrast to leadership within large corporations where the literature indicates that technical skills diminish in relative importance as one rises up the organisational structure while the conceptual skills to devise and implement strategy take primacy (Mumford *et al.*, 2007). Below, in the next paragraph, I discuss whether *actual* technical competence is required or whether the *perception* of technical competence is perhaps more important. At Fermilab, I observed that technical competence retains its perceived importance at all organisational levels. However, there is a change in emphasis on technical competence for senior leaders, where the ability to quantify this competence becomes an important metric. This creates the perception for the laboratory workforce that the senior leader is technically competent. Scientists could claim to substantiate their technical competence through prestigious awards such as the Nobel Prize or being part of new scientific discoveries. Directors seldom interact directly with technology because they spend the majority of their tenure representing the laboratory to stakeholders. A senior leader such as a director often delegates significant authority to a middle manager, such as a project leader, to manage the project as they see fit. This justifies my observation that a second characteristic of leaders at Fermilab, identified in Section 4.2.2, was managerial ability. Both case studies revealed that leaders required a certain level of management ability to be able to implement the chosen strategy or vision. While it was not always possible for a leader to embody both leadership and management, the leader frequently selected a support team to complement his own skill gaps or weaknesses. Those individuals with very specific management skills could be selected for administrative work such as budgeting in order to realise the director’s vision, in the case of the Fermilab associate directors. Therefore, while the perception of technical competence is an important component of leadership in megascience projects, within the laboratory organisation there are also opportunities for individuals with a broader range of non-technical competence. For example, as I noted in Section 4.2.2, one individual with business acumen was put in charge of the Fermilab technology transfer office.

The interviewees at CERN also identified technical competence as creating a foundation for respect. This requirement was common to leadership in accelerator construction and the experimental collaborations, where I classify the project leader, departmental heads and experimental spokespersons as middle managers, rather than being limited to the problem-focussed leaders. With a major project, the breadth of technical competence required was such that it was impossible for a project leader in a middle management role to be a world-leading expert in every relevant field In this case, the deep technical competence of the project leader could be limited to the key technologies. In the case of the LHC, these key technologies were the magnetic and cryogenic systems. The interviewees described the LHC project leader, Lyn Evans, as being one of the best magnet physicists in the world – making him an ideal choice for satisfying this desire for a technically competent leader.

The second characteristic of leaders in the LHC was their management ability. Within the CERN framework, leaders must embody the characteristics of both leadership and management to inspire teams with a common goal, keep the team focussed, and very importantly to maintain the trust of the CERN Council. Leadership and management had a symbiotic relationship – leadership created the sense of common purpose needed to build new facilities while management ensured smooth operation of those facilities. In middle management roles, as with senior leadership positions, it was possible to select management specialists to manage particular processes. Department heads in particular recruited management specialists, freeing themselves to focus on resource acquisition and achieving goals – a process memorably described by Interviewee C12 as ‘filling in personal gaps’. However, the LHC project leader, Lyn Evans, needed to be able to demonstrate to the CERN Council that the project was both on-schedule and on budget. This was to retain the trust of the CERN Council – with the trustworthiness of a leader as an importance characteristic. As I noted in Section 5.2.3, rather than using punishments or rewards, at CERN trust serves to bind individuals together into teams. Each individual within a team has to trust that everyone else will fulfil their role, otherwise they cannot focus on their own task. When someone was given trust by their leader, they were motivated to demonstrate that they were worthy of that trust. Yet, there was also the risk that that trust could be lost with many of the actions taken during the LHC being taken in the context of retaining the trust of the CERN Council. Although I chose to re-phrase it as ‘respect for the team’ in the Fermilab case study, the broad theme of trust remains as an important component of leadership during the construction of the Tevatron. Trusted individuals at Fermilab were granted the freedom to exercise their own judgement when determining how to achieve technical and project goals.

There are considerable similarities between the findings from these two case studies. Firstly, both organisations attach great importance to technical competence as a foundation for leadership. Many renowned experts at both Fermilab and CERN served in middle management roles such as project managers where the technologies had strong links with their own core competence. Notably, the Tevatron I project manager, Helen Edwards, and the LHC project leader, Lyn Evans, were described as the best in their respective fields. This speaks to the high tech nature of the projects, with the underlying technologies heavily influencing the project organisation by the laboratories (Merton, 1942; De Solla Price, 1963). The project managers in middle management roles tended to be more representative of the laboratory style of leadership than the senior leaders, who I consider below. Although, technical competence is an important component of leadership, there are limitations to the breadth of technical competence that is feasible. In these megascience projects, many of the technologies are being applied on a scale never seen before or the technology is being developed in the context of application. This is defined by Shenhar and Dvir (1996) as a class ‘C’ or class ‘D’ project respectively. However, the breadth of technologies is so broad that it would be impossible for any project leader to be technically competent in *all* the relevant fields. Therefore, the interviewees concurred that it is sufficient for the leader to be technically competent in just the key technologies required to realise the project and have a broader understanding of other issues. In the case of both machines, these were the magnet and cryogenic systems, which were by far the most technologically uncertain aspects of the colliders.

However, there are also differences in the leadership characteristics at the two laboratories. One was the organisational level where management ability became an important component of leadership. It was apparent that leaders at all organisational levels at CERN required some degree of management ability, although the application of these abilities varied depending on the specific organisational level. This was not the case at Fermilab, where there was a general suspicion of management. At Fermilab the acknowledgement that managers had to undertake the necessary administrative processes to ensure smooth running was not appreciated below the senior leader level.

With regard to senior leaders, namely the directors of Fermilab and Directors-General at CERN, there was a great deal of similarity. This is not particularly surprising, since it is unlikely that the geographic location of a laboratory will greatly affect the required skills for such a senior position. It is more likely that the primary differences will relate to the financial scale of the laboratory, with larger laboratories requiring a director to be more adept at delegation. In all cases, a director-level leader may already have acquired a reputation for very good science. Ideally, prestigious scientific awards validate this reputation. Normally, this reputation is founded upon extensive scientific experience, with all senior individuals who came through academia having been professors. For some of these individuals, such as Wilson and Lederman, this entitles them to be director of a major research laboratory, giving them experience of the practicalities of running a research laboratory. These senior figures also had extensive experience of working to develop policy for science. This is rather unusual because relatively few members of the scientific community tend to engage with the policy-making process. Instead, these senior figures are expected to take up this responsibility in order to ensure adequate resource provision for their peers (Heilbron *et al.*, 1981b; Hoddeson *et al.*, 2008).

Interpreting these findings in the light of the established literature reveals that leaders in megascience projects embody many of the same characteristics as leaders in other highly technical fields. One can deduce that the workforce in a megascience project is similar in certain respects to the workforce in other highly technical fields (Kidder, 1981). Bennis (1984) and Scarnati (1997) stated that the process of becoming a leader forces an individual to develop conceptual and management skills in addition to their technical competence. My findings are broadly consistent with their findings but also point to technical competence as a foundation for respect at all levels, something which has been a longstanding trait of technical organisations (Baumgartel, 1956; Andrews and Farris, 1967).

However, at senior levels of both Fermilab and CERN, most candidates for the laboratory directorship substantiate their competence with prestigious scientific awards. In this way, there is a shift at senior levels from having a deep understanding of the technology to exploiting their reputation to achieving the strategic goals of the organisation. This is also consistent with the existing literature, particularly the leadership skills strataplex discussed earlier (Mumford *et al.*, 2007). I argue that my findings are broadly in agreement with Mumford *et al.* (2007). One significant difference is that my findings indicate that even senior leaders must be perceived as technically competent, while Mumford *et al.* (2007) found that technical skills diminish in relative importance at higher organisational levels.

Below I explore the findings from each case study in relation to the five leadership styles and discuss what additional leadership characteristics emerge. To remind the reader, these leadership styles are transformational, transactional, laissez-faire, authoritarian, and democratic leadership.

6.2.2 - Transformational leadership

As I discussed in Section 2.2.1, a transformational leader exploits a charismatic communication style to achieve a revolutionary new vision of the future (Bass, 1990).

The interviewees from Fermilab believed that transformational leadership, considered in Section 4.2.4, was highly appropriate in megascience projects. As I noted in Section 4.2.4.1, twelve interviewees identified the two directors, Robert Wilson and Leon Lederman, as transformational leaders. The Tevatron was one component of Wilson's vision, which lasted through Lederman's tenure. At other levels of the organisation, while a charismatic communication style could be beneficial for motivating teams, the ability to implement change became more important. Through the discussions with Fermilab interviewees, I identified that vision and charisma are important characteristics for senior leaders in megascience projects. However, while the vision is essential for these senior leaders, it is redundant for leaders elsewhere as they must act to realise this vision.

The interviewees at CERN also considered transformational leadership to be a fundamental component of leaders in megascience projects. However, the origin of the vision proved to be an interesting point of discussion with the interviewees. The general opinion amongst these interviewees was that a vision could be 'inherited' from another leader. For example, the interviewees associated the LHC with the first Director-General, Carlo Rubbia, who launched and defended the collider against alternatives. After the end of his tenure, subsequent Directors-General sought to realise his vision for the LHC.

As Bass (1990) identified, transformational leaders use a vision to gather followers and inspire them to realise this vision. At CERN, this transformational leader was Carlo Rubbia, who was regularly credited by the interviewees in Section 5.2.6.1 as launching the LHC. At Fermilab the origin of the vision for the Tevatron is only slightly less clear. As noted in Section 4.4, Lederman conceived the original concept underlying Fermilab, namely the 'truly national laboratory' (Lederman, 1963). Wilson took this idea, namely that a national laboratory should be open to all researchers, and turned it into his own vision for the Tevatron. The visions developed by Rubbia and Wilson permeated their respective laboratories and other scientists were motivated to achieve their visions for their respective accelerator. However, it was not necessary for leaders at every level of the project to develop their own visions, because the project teams had already aligned themselves with the senior leader's vision. It is therefore unnecessary for a leader at every single level to have an individual vision because one can be 'borrowed' from elsewhere in the organisation. The first senior leader in the 'conception' phase devises the vision which permeates the entire laboratory. Subsequent senior leaders can make minor changes to the vision to make it achievable but it is not necessary to create a brand new vision as one already exists. Leaders in middle management and problem-focussed levels likewise can ‘borrow’ the senior leader’s vision as their ultimate goals are to realise the vision.

As noted in Section 2.2.1, a transformational leader must be able to implement this vision to demonstrate a record of delivering on their promises (Tracey and Hinkin, 1998). A leader without such a record is viewed with scepticism as individuals question whether such a vision can ever be realised. On this particular issue, my findings are broadly consistent with the literature, which states that transformational leaders need to be able to deliver on a vision (Tracey and Hinkin, 1998). In the case of senior leaders, the laboratories go to great lengths to ensure that directors/Directors-General have a strong record of successfully delivering on their strategies at previous laboratories. Both Rubbia and Wilson had records of successful experiments and constructing accelerators on time and even under budget (Krige, 2001; Hoddeson *et al.*, 2008). In Section 6.4, I address the specific topic of selecting a senior leader to undertake a specific project phase. However, most of the work to realise the vision is effectively outsourced to appointed project managers/leaders in the middle management level, while the senior leader generally allows the project to proceed without intervention unless there is a significant issue that could risk the loss of the trust of stakeholders.

The literature that I considered in Section 2.2.1.1 describes the importance of the charisma that the leader can use to gather a group of followers (Kirkpatrick and Locke, 1996). However, the literature also notes that it can be necessary for the transformational leader to assume a more transactional leadership style in order to realise this vision (Kirkpatrick and Locke, 1996; Tracey and Hinkin, 1998), which I consider below. While the evidence from the two case studies tends to support this theory, it is also possible to introduce a different leader with the required transactional characteristics to have the same effect. This occurred in both the Tevatron and the LHC, where the first leader for the respective accelerator devised the vision, with subsequent leaders selected to realise this vision.

6.2.3 - Transactional leadership

As I observed in Section 2.2.2, transactional leaders operate within an existing culture, using the prospect of reward or punishment to achieve their aims (Bass, 1990). Transactional leaders tend to manage by exception and only intervene when performance drops below what the leader deems reasonable (Bass and Avolio, 1993). In this way a transactional leader maintains a focus on a consistent output to meet specific criteria.

The interviewees felt that transactional leadership was generally inappropriate in megascience projects. The interviewees at Fermilab strongly felt that transactional leadership was inappropriate in megascience projects. They argued that scientists are highly intelligent and creative individuals working at the limits of human knowledge. Therefore, one of the principles of transactional leadership, using rewards or punishments to induce compliance is considered insulting to scientists who are generally motivated purely by science. Within this is the implicit theme that scientists are somehow different from other types of workers. Yet the interviewees also documented instances of successful transactional leadership; as considered in Sections 4.2.5, accepting that it was possible to be transactional towards the end of a project.

At CERN, there was a more relaxed attitude to transactional leadership when handling teams, the general opinion being that it could be useful for busy leaders who had insufficient time to monitor their team. Allowing a team to proceed without interference, unless a particular issue emerged, freed the leader to focus elsewhere. Therefore, transactional leadership was often the product of a heavy workload where leaders had little spare time. In both case studies, while there was a debate over the appropriateness of transactional behaviours towards people, the interviewees identified some utility for transactional leadership during project management. This suggests that it may be ineffective for leading scientists, but in a situation where the human element can be ignored in favour of total project focus, it might be useful. This dismissal of the human element may have contributed to some negative perceptions of transactional leadership, given that several interviewees claimed it would not work, but also failed to justify these preconceived notions. The interviewees deemed the application of transactional leadership especially appropriate towards the end of a project, as the key technical challenges should have been already resolved. The absence of residual challenges allows project leadership to focus more on adhering to the project budget and timetable. This contrasts with the early project stages, when there is a greater degree of technological uncertainty.

Here there is a difference between attitudes and practices. On the one hand, the interviewees claim that scientists are special and transactional leadership is insulting. On the other hand, most of the interviewees have observed transactional leadership amongst project managers. As the literature has suggested, science can be a technically uncertain process. For example, the data may not fit with theoretical predictions or there may be equipment malfunctions (Hoddeson, 1992). Many scientists will have experienced such issues, which endow them with a tolerance of ambiguous issues that are resolved as the project progresses. Transactional leadership requires an assumption of well-understood issues at the beginning of a project (Bass, 1990; Tyssen *et al.*, 2013). Any ambiguity brings into question the value of timetables and budgets, for instance, since these can raise unforeseeable issues which in turn can force substantial delays (Shenhar and Dvir, 1996). This conflict between the scientists who are comfortable with ambiguities to be resolved at a later point, and the desire of a transactional leader for well-understood tasks probably is the reason that the interviewees had concerns over the applicability of transactional leadership. Regarding transactional leadership in project management, Kirkpatrick and Locke (1996) theorised that a transformational leader may have to assume a more transactional style to close out projects in order to build a base of credibility. Here the interviewees at both Fermilab and CERN are broadly in agreement with the literature that, towards the end of a megascience project, most of the important technical issues have generally been resolved and project leadership can focus on staying on time and on budget. This is why I chose to designate transactional characteristics, specifically with regards to a focus on keeping to schedules and budgets, as one of the characteristics of leaders within megascience projects, although this is usually restricted to middle managers at project end-stages. The principle of ‘management by exception’ is not deemed a characteristic of leaders within megascience projects as it was considered insulting to the scientists.

The issue of ‘shocks’ was identified by the CERN interviewees in Section 5.2.1 as an area of concern. The Fermilab interviewees did not regard shocks as such an important issue. This is likely because the fieldwork identified no major shocks once the Tevatron construction phase began, while the 2008 LHC magnet quench incident did constitute a substantial shock.[51] Such a shock proved to be a source of concern over transactional leadership at the end of a project. If a shock were to occur, they believed that project

[51] There were several technical issues during the Tevatron programme but they these were relatively minor and hence did not constitute a shock event. While Wilson’s resignation certainly did constitute a shock, this took place before construction of the Tevatron began.

leadership should not continue to pursue transactional leadership because the shock would fundamentally change the situation. This is the reason why the CERN Accelerators head, Steve Myers, did not seek to manage this particular shock using a transactional leadership style but rather attempted to gain a full understanding of the issues. This required lengthy investigation and repair, which resulted in the LHC operating at a much lower energy than originally expected, in order to avoid a repeat occurrence, despite the risk that this might have made it impossible to detect the existence of the Higgs boson.

6.2.4 - Laissez-faire leadership

In this section, I discuss the attitudes held by the interviewees concerning laissez-faire leadership, which involves leaders who generally permit groups to set targets and methods, allowing work to progress with little intervention (Bass, 1990; Woods, 2004). The interviewees at Fermilab initially expressed a rather negative reaction to the idea of laissez-faire leadership, as we saw in Section 4.2.6. Several interviewees described it as a form of leadership that abdicated responsibility and that it would not work in a laboratory, where leaders had to be actively involved with their team. However, during the discussion, several of these interviewees moderated their statements and said that a leader could be laissez-faire in certain circumstances. These circumstances included where a leader lacked technical competence in a particular situation. The Fermilab interviewees argued that in such a situation it was acceptable to delegate decision-making to the team if it had a greater technical competency. Equally, laissez-faire leadership could also be the result of a leader focussing on certain issues. For example, Wilson's laissez-faire attitude in the early life of Fermilab allegedly was the product of his focus on building laboratory facilities and assumed that an experimental community would naturally appear. Some interviewees at Fermilab even suggested that laissez-faire leadership could be the product of an intentional strategy - when the team was working well, then the leader should allow the team to keep working and let it determine how to complete tasks. This is the reason why I described team empowerment as a characteristic of leaders during the Tevatron.

There was a similar situation at CERN, described in Section 5.2.8. The interviewees described laissez-faire leadership negatively, with many interviewees questioning whether it was even a form of leadership at all. However, three CERN interviewees claimed that it could be useful to be a laissez-faire leader when leading a particularly competent team. It suited both parties – by empowering the team, they gain the freedom to learn for themselves, and the leader can focus on other activities such as acquiring resources for future tasks. This explains my reasons for identifying team empowerment as a characteristic of leaders at the LHC.

The literature on laissez-faire leadership frequently claims that it is the least effective leadership style, which benefits neither the leader nor the follower (Bass, 1990). Some notable authors have observed exceptions to this rule (Baumgartel, 1956; Andrews and Farris, 1967; Mumford *et al.*, 2002). Andrews and Farris (1967) claimed that the 'ideal' supervisor was one who was technically competent in the task. If such a technically competent leader did not exist, it was wise to give the team significant freedom (Andrews and Farris, 1967). However, this freedom had to have certain bounds and the leader should act to keep the team within these limits, for example by ensuring the work aligned with organisational goals and by providing opportunities for team members to critique each other's work (Andrews and Farris, 1967; Mumford *et al.*, 2002). My findings are mostly in line with these observations from the literature. Although the ideal team leader was technically competent in the areas under investigation, certain notable exceptions emerged during the fieldwork. For example, when the technology was brand new, as Interviewee F3 notably found that it was impossible to understand all the technologies under investigation, the team leader acted to empower the team while ensuring adequate resource provision. Laissez-faire leadership was also the product of a heavy workload; leaders frequently lacked the time to engage with teams, so they sought to liberate the team to prevent a bottleneck. However, as I noted in Section 6.2.1, the trust that the leader gave their team during such an exercise was valuable and the team was very reluctant to risk losing it. This was notably the case for Interviewee C7 went to great lengths to avoid losing the trust of his leader, and for Interviewee C1 who exploited the risk of losing trust to get non-member states to keep to their promises.

6.2.5 - Authoritarian leadership

During the fieldwork, a contradiction became apparent when discussing authoritarian leadership with the interviewees. While the interviewees initially did not consider authoritarian leadership to be appropriate in megascience projects, during subsequent discussions they often proceeded to give examples of successful authoritarian leadership, with additional evidence of this in the literature (Taubes, 1986; Taubes, 2003; Riordan *et al.*, 2015).

At Fermilab, I identified in Section 4.2.7 that there was a general acceptance of authoritarian leadership. The interviewees were broadly accepting of authoritarian leadership provided the leader made the right decisions for the laboratory. The two directors over the lifetime of the Tevatron, Robert Wilson and Leon Lederman, exercised some authoritarian tendencies by taking personal control in matters when a different director might have delegated. Such an example relates to the discussions around Wilson getting personally involved in very technical decisions related to the Tevatron, even when these proposals subsequently had to be changed to become workable (Hoddeson *et al.*, 2008)

The interviewees described in Section 5.2.9 the culture at CERN as being incompatible with the notion of authoritarian leadership. While authoritarian leadership might prove successful in the short-term, it could result in long-term damage and an exodus of talent. Yet despite these assertions, there were several instances at CERN where authoritarian leadership was a demonstrable success for several years. One such instance was the first Director-General during the LHC project, Carlo Rubbia, cited as a clear example of authoritarian leadership in the literature (Taubes, 1986; Taubes, 2003). The interviewees suggested that a crisis could force the scientific community to sacrifice their traditional autonomy for an authoritarian leader. To rephrase a quote from Section 5.2.9, the community was willing to look past the authoritarianism because they believed he could deliver.

Both Fermilab and CERN interviewees agreed that authoritarian leadership was generally inappropriate within science. Their arguments were that it might bring short-term benefits but it would alienate staff and drive out talent in the longer term. Yet there was evidence that despite these strong objections, authoritarian leadership was successful and indeed that it was on several occasions. These were not limited to the Tevatron or LHC. Samuel Ting, a well-known experimental particle physicist, has also been described in similar terms (A more detailed summary of Ting is in footnote 49) (Riordan *et al.*, 2015). But, these individuals are regarded as exceptional which is why I was unable to use the heterogeneous engineer as a foundation for broader leadership theory. Therefore, I do not regard authoritarian leadership as a general characteristic of leaders in megascience projects.

In relation to the literature, these observations are partly consistent with the work by Likert (1977), who sub-divided authoritarian leadership into two distinct categories. As we saw in Section 2.2.4, the two sub-categories were punitive authoritarian and benevolent authoritarian leadership. Punitive authoritarian leaders emphasise threats of punishment while benevolent authoritarian leaders exercise more positive reinforcement for teams (Verma, 2014). On this basis, the scientific community perceive authoritarian leadership as solely being the former type while many of the authoritarian leaders they met are mostly of the latter type. This perhaps explains the gulf between the perceptions of the interviewees and personal experiences. Throughout the process of conducting my research, there was an underlying assumption amongst my interviewees that scientific projects are somehow different from other projects. However, the finding that scientists are sometimes receptive to authoritarian leadership suggests that this assumption was incorrect. Scientists can in fact be receptive to authoritarian leadership, similar to high tech workers (Kidder, 1981). Both parties traditionally desire the freedom to determine their own methods of achieving goals, but in exceptional circumstances, they are willing to sacrifice this freedom to a strong leader if they believe this leader can deliver on their promises.

6.2.6 - Democratic leadership

As discussed in Sections 4.2.5 and 5.2.10, the interviewees expressed a strong preference for democratic leadership. This was especially pronounced at CERN, where the ideal decision was based on consensus. However, democracy had its limits and some interviewees put forward the important concept of ‘guiding’ the team towards what was deemed to be the correct decision.

During the construction phase of the Tevatron programme, the director had significant power but delegated it to appointed project managers. Although there was a change of director before construction began, this was caused by an unexpected political and financial shock rather than a resignation driven by strategy. However, this unexpected event still led to a leadership change that brought in the necessary skillset to get the Tevatron programme approved. As the programme comprised three projects, there is a trio of project managers to consider. All three of the Tevatron project managers were described as extremely technically competent, even the best in their respective fields. The project managers did not seek to build consensus preferring to focus on getting the project completed within acceptable parameters. The interviewees described the project manager for Tevatron I (the colliding beams project) in particular as a democratic leader with some transactional characteristics.

The democratic ideal permeated CERN and collaborations associated with the LHC. However, while it was possible to delegate tasks, the leader retained responsibility for success. The importance of each task was such that any issue could cause a delay to project completion and damage the reputation of a leader and ultimately the reputation of Lyn Evans, the LHC project leader. This forced all accelerator section/group leaders (which I consider to be problem-focussed leaders according to my three level model) to delegate wisely and trust that the team could complete the work; fortunately, these leaders had the control of resources necessary for them to assert their authority when necessary. This also meant that the LHC project leader, Lyn Evans, who controlled the resources directly, could manage the construction project using appropriate project management tools. This was not the case with the experimental collaborations. Both the accelerator constructors and the experimental collaborations aspired to the ideal of democratic leadership. However, while the LHC project leader, Lyn Evans, had centralised control over resources, an experimental collaboration spokesperson has very little control over collaboration resources. The majority of financial control rested instead with collaborators who could freely leave the collaboration, withdrawing their resources and suffering no major consequences. Therefore, the democratic leadership ideal held by the collaborators and the widespread observations of democratic leadership were not just altruistic but reflections of financial reality. Despite the strong affinity for democracy, the interviewees did not deem democracy a perfect mechanism for decision-making, and several of them put forward, instead, the idea of ‘guided democracy’ as a means to limit the potential choices on offer in a discussion and persuade teams to make the 'wise' decision. The interviewees understood that democratic leadership is part of a process where the collective retains power, but the unexpected finding was that the interviewees suggested a method of political governance to subvert this process – guided democracy. Below, I briefly describe to what this unexpected term ‘guided democracy’ refers and how it has been adapted to fit the context of experimental particle physics collaborations.

The literature on ‘guided democracy’ usually refers to a system of political governance, developed in the 1920s and implemented in 1950s Indonesia (Lippmann, 1922; Feith, 2006; Lev, 2009). This system brought all interested parties into discussions to achieve political consensus as Western-style democracy was critiqued by the Indonesian President as leading to scenarios wherein "…51% wins and 49% ends up with a grudge" (Kanalgalingam, 1997; Lev, 2009). However, as the President also chaired this council, it significantly tightened his grip on power. Likewise, the experimental particle physics collaborations have sought to implement similar mechanisms that allow open debate while limiting the choices to those deemed 'reasonable' by the spokesperson. Thus, the spokesperson has significant leadership influence to guide discussions toward their desired outcome. The use of guided democracy in an experimental collaboration effectively preserves democracy at the most task-centric levels of the collaboration, while ensuring that a collaboration spokesperson can direct overall policies. Exploitation of the concept of a guided democracy was one of the characteristics of leaders in experimental collaborations. Descriptions of guided democracy in experimental collaborations are limited in the literature, one being the brief identification of a form of guided democracy existing during the construction of an early accelerator at CERN during the 1950s (Krige, 1997).

6.2.7 - Leadership in accelerator construction compared with experimental collaborations

The LHC experimental collaborations reveal a very different form of leadership, one required because of the financial arrangements by which resources flow 'up' from the collaborating institutions to where they are required. In this case, a more democratic consultative collaboration spokesperson is required even if the leader must occasionally take steps to guide the collaboration. In this environment, the leader must act to guide debate and steer fellow collaborators towards consensus, ideally on a scientific basis. The interviewees likewise reached a consensus that the spokespersons who led the experiments were highly democratic, although as discussed above in Section 6.2.6, some 'guided democracy' was required to prevent teams running out of control.

The senior leadership of an entire laboratory, such as the Fermilab directors or the CERN Directors-General, benefits from new leaders appointed specifically to meet phase-specific needs of the project. A leader who secures project funding might not be the most suitable for overseeing the construction effort once the initially uncertain issues become better defined. Section 6.4 addresses this topic.

Megascience projects, particularly accelerator construction, tend to embody the characteristics and leadership styles of large projects rather than representing a synthesis of the leadership styles seen in technologically uncertain projects and large projects. To briefly reiterate from Sections 2.4.3 and 2.4.4, megascience projects appear to be a subcategory of large projects that incorporate many of the characteristics of technologically uncertain projects in that they incorporate the first use of technologies or even technologies developed in the context of application.

The experimental collaborations at CERN, in contrast, generally took no measures to reduce the technological uncertainty of the project; Interviewee C15 even suggested that they attempted to innovate until the very last minute. For example, during a minor delay to the restart of the LHC in 2015, the experimental collaborations took the opportunity to make adjustments to the computer code that controlled the detector (Webb, 2015). The 2008 LHC magnet quench incident also provided additional time for detector calibration (Brumfiel, 2008). The experimental collaborations therefore embody more of the characteristics of technologically uncertain projects than of large projects. These technologically uncertain projects were considered by Shenhar and Dvir (1996) to require greater tolerance from leaders towards delays and budget overruns. This would explain why the interviewees from the collaborations failed to cite such delays as being particularly important. On the other hand, the timetable for completion of accelerator construction effectively dictates the timetable for the experimental detector, with any delays offering an opportunity to improve the detector. For the most part, this thesis has served to confirm the findings of Liyanage and Boisot (2011) as it demonstrates the generalisability of their findings from ATLAS to CMS. However, their work did not identify the existence of guided democracy.

6.2.8 - Summary of the characteristics of leaders in megascience projects

To summarise the answer for the first research question, there are multiple characteristics of leaders in megascience projects. These include technical competence, management ability, charisma, a vision, team empowerment, and the ability for individuals to exploit some of the style and rhetoric of democracy while actually taking steps to control decision-making. These characteristics varied in importance according to the place of the organisation in which the leader was working (See Table 6):

Characteristic	Restrictions
Technical competence	Essential for all leaders at all levels
Management ability	Observed at all levels but essential for middle managers
Vision	Essential for first senior leader, less important for subsequent senior leaders. Redundant for leaders elsewhere
Charisma	Important at all levels
Transactional characteristics (Keeping to budgets and schedules)	Important for middle managers towards the end stages of a project
Guided democracy	Only observed amongst leaders within experimental collaborations
Team empowerment	Important for all leaders
Trustworthiness	Essential for all leaders and their teams, links to team empowerment

Table 6: A summary of the characteristics of leaders in megascience projects and which levels these characteristics were observed

6.3 - Where and how were their leadership skills developed?

In Section 2.6, I concluded that it was interesting from both academic and policy practitioner perspectives, to understand how and where leaders in megascience projects developed their leadership skills. This additional information is of value to the leadership literature and can inform leadership training programmes for laboratories in the future.

At Fermilab, the interviewees regarded formal training programmes with suspicion, as reported in Section 4.3.1. This was derived from the 'ambivalence to control' that characterised the frontier-like culture that Wilson sought to create in the establishment of Fermilab (Hoddeson *et al.*, 2008). However, a somewhat different identification and cultivation mechanism evolved to account for these cultural factors - leaders would identify potential future talent and quietly cultivate these talents. Certain laboratory positions were utilised to give identified individuals practical experience in leadership. In this case, the *where* and *how* leaders developed at Fermilab was within the laboratory framework in the form of gaining practical experience in specific leadership positions.

This mechanism seemingly evolved to compensate for the cultural aversion to centralised leadership programmes.

At CERN, a combination of practical experience and courses cultivated future talent. These courses, offered once an individual reached the first ‘rung’ of the CERN management ladder, sought to provide tools and an understanding of how to lead within the CERN framework. Although the interviewees did express some concerns relating to the CERN administrative workforce, these were over the risk of introducing inefficiencies because of an excessively large team of coordinators. In this case, the *where* and *how* leaders developed at CERN was also within the laboratory framework, but using practical experience and classroom training delivered in combination.

Thus, in both the Tevatron and the LHC, the majority of leaders received their training within their respective organisations. The project to construct each new collider focussed solely on the construction of new facilities. The development of leadership is not a core responsibility of these two megascience projects, so instead the laboratory organises training provision. However, the LHC experimental collaborations, which operate with budgets similar to the accelerator construction projects, viewed the identification and development of the next generation of leaders as a core part of their work. It often required a leader, usually a problem-focussed one but occasionally a middle manager, to recognise a talented individual and mentor them. Many of my interviewees used a rather simple method to identify future leaders. As I discussed in Section 5.2.1, these interviewees usually began to notice a future leadership prospect by observing their team frequently deferring to the technical competence of an individual. This is a good example of the importance of technical competence within megascience projects, as it became the primary indicator or means to identify future leaders.

In contrast, the most senior leaders, such as a director or Director-General, did not normally receive training within the laboratory framework, and did not undergo this ‘cultivation’ process outlined in the above paragraph. Furthermore, they have rarely spent long periods as a laboratory employee but several may have served as senior experimenters or as part of the laboratory governing council. This presents more of a challenge in determining the nature of their development as leaders.

Although these senior leaders may not have spent long periods working at the laboratory, they generally have a long-standing relationship with it which often comes from serving as external auditors or prominent members of the laboratory community. In the United States, such prominent members of the experimental community are often high on any shortlist when considering potential new directors, as with Lederman during the construction of the Tevatron.

At CERN, I observed a different phenomenon, whereby Directors-General receive training in the form of a transitional year after their selection by the CERN Council but before the start of their formal tenure. This is similar to the Fermilab principle of learning through experience, although at a much higher level within the organisation. Furthermore, the Directors-General usually played a major role in the laboratory despite no formal employment by the laboratory; for example participation in the laboratory policy-making process. In these situations, they gained an understanding of the CERN model of policy-making and strategy and an awareness of the key issues confronting the laboratory. While only a single LHC Director-General was 'internally promoted' (i.e. became Director-General while currently employed by the laboratory), one other internal candidate has subsequently risen to Director-General. In both cases, the successful candidate came from an experimental collaboration. This indicates that selection panels and the CERN Council decided that the characteristics of experimental collaboration spokespersons, who traditionally seek to discuss and reach consensus, are also well suited to the position of Director-General.

The conclusion is that Directors-General act to represent the community, rarely taking direct action unless the situation warrants it. It also suggests that, in certain situations, a Director-General could guide the CERN community towards what they might consider the appropriate course of action. Rubbia certainly demonstrated this by uniting the laboratory around the LHC as 'the next big machine', even when alternative colliders elsewhere offered an apparently superior arrangement (Fraser, 1997; Smith, 2007; Riordan *et al.*, 2015).

In summary, training for problem-focussed and middle management leaders is conducted within the laboratory using practical experience as the main training tool with formal training programmes in the CERN case acting as a support tool. For these particular leaders, this training begins after being identified by a more senior colleague and receiving opportunities to develop their leadership skills. Senior leaders usually work at universities or other research institutes. By following the academic route, these leaders become involved in developing policy for science.[52] This process of using their conceptual skills brings them into the domain of science policy. This experience is important when selecting new senior level leaders, but it is possible to create an apprenticeship year to provide on-the-job experience. Most other scientists, particularly within accelerator construction, remain discipline-oriented.

6.4 - Tailoring the selection of different senior leaders for specific phases of the project

One particular insight emerged during the fieldwork. This insight was that the laboratories had pursued a strategy, whether deliberately or subconsciously, to select senior leaders (directors in the case of Fermilab, Directors-General in the case of CERN) in part to meet phase-specific needs of the project. This practice emerged more distinctly at CERN because of the convention that senior leaders serve a single five-year term. While Fermilab had significantly longer directorships, the practice still existed in a certain form. This is addressed below.

In Section 4.4, I dealt specifically with the issue of the Fermilab directors. To refresh the reader's memory, Wilson incorporated the Tevatron into his original vision of Fermilab but he was not well suited to engaging with the cost-conscious 1970s US government. On the other hand, Lederman could engage with the US government to secure the funding for the Tevatron. Although Lederman did not resign to allow a new director to oversee the construction, he did demonstrate that such phases still existed for the Tevatron by delegation of a significant amount of the construction work to appointed project managers. Even as the scientific community was just starting to use the Tevatron, consideration was also given toward what the 'next big machine' would be (Hoddeson *et al.*, 2008; Riordan *et al.*, 2015). This proposed machine was the Superconducting Super Collider (Riordan *et al.*, 2015). These observations suggest that the scientists are in a constant cycle of proposing new accelerators, getting government approval, and construction. This is of particular relevance to the phases of megascience projects that I consider below in Section 6.4.2.

[52] I chose to phrase it as 'policy for science' rather than 'science policy' to reflect the specific niche. While science policy involves a wide variety of studies including patent analysis, energy policy, and industrial policy to use science to help improve society, 'policy for science' examines solely how government policy can support scientists.

While a more detailed description of these individual Directors-General is in Section 5.4, to reiterate, there were four Directors-General over these phases. Carlo Rubbia who secured the LHC's place in CERN's strategy, Christopher Llewellyn-Smith who turned the LHC from a concept into a feasible reality, while Maiani and Aymar mostly allowed the project leader to manage the project as he deemed fit. Currently, the CERN community is considering what the 'next big machine' will be (Rossi, 2016). Every five years, when the position of Director-General became available, selection panels have the opportunity to choose a candidate suited to the needs of the project.

An examination of the literature suggests that this particular concept of selecting different leaders to suit a specific project phase is difficult to explain using the style leadership paradigm. These style paradigms, considered in Section 2.2, do not focus on the process of leadership selection. Contingency theory, one of the evolutionary leadership paradigms briefly examined in Section 2.3.4, arguably aligns rather better with the selection of a specific type of leader for a particular situation. To reiterate, contingency theory classifies the leader and the situation according to a set of criteria (Fiedler, 1964). The classification of a potential leader and the situation introduces the ability to 'match' an appropriate leader to a given situation. This provides an insight into the process through which selection panels go to tailor the selection of the senior leader to the phase of the project.

6.4.1 - Classifying the megascience project senior leader and situation with contingency theory

In this section, I explore the process that a selection panel would go through when classifying a potential senior leader and situation according to the criteria in Section 2.3.4. When classifying a leader utilising the Fiedler (1964) Least Preferred Co-worker scale (LPC), the leader must be categorised based on their level of task or relationship-motivation.

Briefly summarising the literature from Section 2.3.4, task-motivated leaders judge their own success by whether the project is successful while relationship-motivated leaders seek to facilitate interactions on the assumption that they may improve solutions (Fiedler, 1964). Based on this, it becomes clear that the final two Directors-General of the LHC project were task-motivated. This arises because by their tenures, most technical issues had been resolved and the remaining concerns related to completion of the LHC while maintaining the trust of the CERN Council. Llewellyn-Smith and Lederman, who secured the necessary funding for the LHC and Tevatron respectively, were relatively more relationship-motivated but retained a focus on the project itself. While Lederman at Fermilab did not resign in favour of a more task-motivated director following the approval to construct the Tevatron, he still represented the change in phase by heavily delegating the construction to three appointed project managers. These three project managers were more task-motivated than Lederman.

The classification of Rubbia and Wilson, who were deemed the 'fathers' of their respective accelerators, led me to conclude that they were more task-focussed leaders, as both focussed on securing the place of the machines in the strategy of the laboratory. As the selection panels for senior leaders occasionally have the opportunity to focus on the needs of the project in the medium term (five years), one could argue that they are primarily problem-focussed rather than driven by the character of the potential senior leader. Therefore, I would argue that a task-motivated leader is usually viewed as more desirable by selection panels. This maintains the focus on the project. While a relationship-motivated leader could be useful at times, such as the cases of Llewellyn-Smith and Lederman, both leaders retained a task-motivation and the building of alliances was ultimately a means to an end.

These selection panels will likewise have to classify the situation using the various parameters described in Section 2.3.4. The following seeks to apply these principles of contingency theory to determine the situation that a senior leader will find themselves in. To reiterate, these parameters were the leader-member relations, task structure, and position power. The literature refers to the process as classifying the 'situation' (Fiedler, 1964).

Leader-member relations classifies the atmosphere of the group and its attitude toward the leader (Mumford *et al.*, 2000). Although the leader-member exchange (LMX) is one important component of leader-member relations, it requires communication between a leader and the team members. It is not feasible for a senior leader of a laboratory with thousands of employees to engage in an interactive discussion with every single employee. This makes it rather difficult for the relationship to progress to the 'acquaintance' or even 'partnership' level theorised by Graen and Uhl-Bien (1995) and which I described in Section 2.3.4. Furthermore, the experimental community associated with a laboratory may not spend much time at the laboratory, often being based in universities or other research laboratories. Therefore, for the majority of employees most communications with the senior leader will be unidirectional in ‘town hall’ style meetings. These meetings, which also exist in politics, involve the senior leader sharing their plans and giving the workforce the opportunity to question him on a variety of subjects (Bryan, 2010). However, a key issue is to ensure that the laboratory staff are receptive and willing to work with the senior leader. As discussed in Section 5.4.4, one Director-General at CERN, Robert Aymar, experienced resistance during his tenure, with one interviewee notably describing him as a military General. By contrast, the interviewees from the Tevatron case study made few negative comments about Wilson or Lederman, indicating that the laboratory was very receptive to their leadership.

Task structure is a measure of the standardisation associated with a particular task (Fiedler, 1964). As discussed in Section 2.4.2, a megascience project may appear to be technologically uncertain with some aspects possessing either a high or a very high level of technological uncertainty according to the Shenhar and Dvir (1996) classification system. However, there will also be more technologically certain aspects of the project, so a stratified assessment may be suitable to determine which aspects of the project require a more tolerant attitude towards cost or schedule overruns. Additionally, the evidence from the two case studies suggests that megascience projects embody more of the characteristics of large projects than of technologically uncertain ones. Therefore, although on first inspection a megascience project may appear to be of a non-standardised nature, upon further investigation I concluded that the majority of the project is fairly standardised, with the primary issue being scale. Although the magnetic systems in both the Tevatron and the LHC were novel features, the laboratory designed the magnets and then passed them to private industry to fabricate.

The paragraph above referred to the construction phase of the project as being relatively standardised, which would suit a highly task-motivated leader. The early phases of a project can exhibit many ambiguities, notably how to secure funding which was an issue for both the Tevatron and the LHC. This provides an opportunity to develop novel agreements. For example, during the process to gain funding for the LHC, the then-Director-General secured agreements with non-member states for the first time. These agreements effectively traded laboratory access in exchange for funding, which then allowed the construction of the LHC to proceed as a single-stage project. Whereas a task-motivated leader such as Wilson faced significant challenges in getting the Tevatron approved by the US government.

Position power refers to the extent to which a leader is able to reward or discipline team members (Fiedler, 1964). An individual with a high level of position power will have greater power over team members and strategy (Fiedler, 1964). In Section 6.4.2, I explore these different project phases that emerged during the fieldwork. These four phases would seem to influence the decision-making process of a selection committee. A position as a Fermilab director or a CERN Director-General is highly influential, although there is a view that such a leader should not act unilaterally unless there is a substantial issue that requires a direct intervention. Effectively, these positions exist to represent the community and chart a broad strategy rather than detailed minutiae.

6.4.2 - The different phases

The finding that the selection of different leaders is partly linked to a particular project phase suggests that selection panels have a conscious or sub-conscious belief that it is possible to match an appropriate leader to a specific phase of a project. Equally, there must be specific phases to enable such a pairing process to occur. As I noted in Section 2.3.4, contingency theory describes a process of 'pairing' situations and leaders, in which selection panels examine the expected strategic needs of the laboratory or project and match an appropriate senior leader. There appear to be common 'phases' within the lifetimes of the two megascience projects I have investigated. Below, I describe these phases and explore the activities undertaken during each one.

6.4.2.1 - Initiation

This is the first phase of the project, where many technical options are explored and eventually narrowed down to a few. From these few remaining options, a single accelerator concept emerges that links together many systems. This forms the basis for the future project. Even during the conceptualisation of the project, senior leaders often get involved in making decisions, particularly when changes in one aspect of the project may have impact elsewhere. A senior leader should have the conceptual skills to understand the issues relating to different systems interface and manage these risks appropriately. Once the accelerator has a relatively fixed design, they seek to secure its place within future strategy by convincing stakeholders of the merits and key role this accelerator deserves within the future strategy of the laboratory. Based on observations from the fieldwork, I have found that laboratories tend to recruit charismatic authoritarian senior leaders during this time to take these decisions and unite the laboratory around this new concept.

6.4.2.2 - Approval

The second phase of the project builds on the previous phase to develop the project beyond a concept into a feasible reality. Senior leaders must further engage with stakeholders to secure funding for the project as well as to develop mechanisms that will allow progress to be measured. In some cases, the negotiation of novel funding or diplomatic agreements allows the project to become feasible. During this time, there is a transition in leadership from the charismatic or even authoritarian style of leadership evident during the initiation phase to a more democratic style. This new leader seeks to negotiate with laboratory stakeholders to secure the necessary funding that will allow the project to move to construction. He or she may also have to engage with non-traditional audiences to open up new funding streams.

6.4.2.3 - Construction

This is the third phase of the construction project, during which senior leaders generally do not directly act to manage the project. Instead, a project manager will oversee the project, and senior involvement will only take place in extreme circumstances that could affect stakeholder confidence. Therefore, it is not always necessary to change the leader to suit this new phase because the project management team has significant autonomy. If there is a new leader for this phase, they will need to have a thorough understanding of the project timeline and understand that their role may require them to act with restraint. However, this phase will require any existing leader to relinquish the control they had during the approval phase and act to support the project management team, ensuring they have adequate resource provision. It is also likely that such a leader will have to act as an early warning system should the project begin to encounter problems, and will need to intervene before external stakeholders become overly concerned. In these situations, the senior leader has to intervene but the scientific community must perceive this as him reluctantly stepping in to avert a greater crisis.

6.4.2.4 - Exploitation

This fourth and final phase begins as the accelerator comes into operation. During this time, the focus shifts towards two new topics. The first is the full exploitation of the completed accelerator. This can involve supporting the experimental collaborations during the first collisions and data acquisition as well as maximising efficiency and enabling any upgrades to maximise accelerator performance. The second topic, ‘horizon scanning’, involves looking towards the future and the next big machine. The term ‘horizon scanning’ is already in use in the literature, particularly in the context of ecology and emerging technologies (Douw *et al.*, 2003; Sutherland and Woodroof, 2009). It is also a concept implemented within the British government as a strategic and policy tool for ‘future proofing’ (Science and Technology Committee, 2014). Horizon scanning in the context of megascience projects involves undertaking studies to determine potential areas of investigation and possible technologies for use in a future accelerator. Although senior leaders generally do not lead these efforts, they must understand that the preliminary work needs to begin soon after completion, and act to support these twin tasks. I observed this at both Fermilab and CERN. At Fermilab, the Tevatron was conceived soon after the completion of the Main Ring and early work on the SSC began even as the Tevatron was still under construction (Hoddeson *et al.,* 2008; Riordan *et al.*, 2015). In the case of CERN, Section 5.1.1 showed that attention quickly shifted toward a large hadron collider concept soon after the completion of the previous major machine, LEP. Furthermore, CERN began investigating a new accelerator soon after the completion of the LHC, as we saw in Section 5.2.6.1 (Rossi and Brüning, 2012). Eventually a new leader emerges, crafts a vision for this new accelerator, and the cycle begins again. In some cases, this exploitation phase may last for many years, especially if the accelerator is not required to be part of the infrastructure for the next ‘big machine’.

A summary of the characteristics of the phases and senior leaders specifically can be found in Table 7:

Phase	Characteristics of phase	Characteristics of phase-specific senior leader
Initiation	Many technical ambiguities. Internal debate over which big machine should form basis of laboratory strategy	Authoritarian. Technically focussed. Very charismatic. Well-suited to transformational or authoritarian leaders
Approval	Internal debate settled around machine. Funding for machine required which necessitates agreement amongst stakeholders	Democratic. Consultative. Seeking to build consensus and trust amongst stakeholders
Construction	Civil engineering and machine assembled. Project leader takes lead role and has freedom to be authoritarian if necessary	Oversight of the project leader. Rarely intervenes except in the event of a major crisis which risks loss of stakeholder trust
Exploitation	Shift in focus: a) Fully exploiting the now-completed machine b) Horizon scanning to determine the characteristics of the next big machine	Support role to help the laboratory and collaborations generate data. Moving resources to help individuals investigate promising technologies for the next big machine.

Table 7: A summary of the phases identified for megascience projects and the characteristics of the phase-specific senior leader

6.4.3 - Mapping the megascience project phases onto the project lifecycles

In Table 8, I map the megascience project phases which I observed against the three models in Table 2. As can be seen, although the megascience project phases do not map perfectly onto any of the lifecycle models, it maps onto the traditional project lifecycle model rather better than either the Wheelwright (1992) or the Gluck and Foster (1975) models. However, the additional ‘exploitation’ phase does not map neatly onto any of the models as it occurs after project completion:

<table>
<tr><th>Project lifecycle</th><th>Wheelwright (1992) model</th><th>Gluck and Foster (1975) model</th><th>Megascience phases</th></tr>
<tr><td>Conceptual</td><td>Knowledge acquisition</td><td>Study</td><td rowspan="2">Initiation</td></tr>
<tr><td>Planning</td><td>Concept investigation</td><td rowspan="2">Design</td></tr>
<tr><td rowspan="3">Execution</td><td>Basic design</td><td rowspan="2">Approval</td></tr>
<tr><td>Prototype building</td><td>Development</td></tr>
<tr><td>Pilot production</td><td>Preproduction</td><td rowspan="2">Construction</td></tr>
<tr><td rowspan="2">Termination</td><td rowspan="2">Manufacturing ramp-up</td><td rowspan="2">Production</td></tr>
<tr><td>Exploitation</td></tr>
</table>

Table 8: An illustrative mapping of how the megascience phases map onto the three project lifecycles observed in Table 2

A second finding that is somewhat in conflict with previous literature is the observation that senior leaders tend to get involved in detailed technical decisions at the early stages of megascience projects and this level of involvement generally declines as the project proceeds. This is in contrast with the literature reviewed in Section 2.3.5 which states that managers, particularly in development projects, do not get involved in early technical discussions but exercise substantial influence towards the end of the project (Gluck and Foster, 1975; Wheelwright, 1992). This ignores the issue that this involvement in the end-stages would be at a time when their ability to influence the final project is rather weak (Gluck and Foster, 1975; Wheelwright, 1992). On balance, this contrast is a result of the deep level of technical competence that is characteristic of leaders in megascience projects. During the initiation phase, there are many ambiguities and the project lacks an appointed project leader. Therefore, authoritarian senior leaders take it upon themselves to get involved in these detailed technical discussions, even if their proposals require amendment at a later point. This was notably the case for both Robert Wilson and Carlo Rubbia at the Tevatron and the LHC respectively. I do not believe that it indicates that all large project ‘clients’ should expend significant effort to completely define the systems that they wish to construct at early project stages. Rather, this issue of technical details should be left to those with the appropriate technical competency. In the case of a megascience project, those experts will be available in-house but for other large projects the client generally lacks this expertise so they should defer to the experts within the delivery partner. However, if these experts can be brought into the client structure at an early point, then large project clients could make use of this finding and define the entire system at an early project stage.

The appointment of the megascience project leader, which usually occurs during the approval phase, is a pivotal moment that marks the senior leader's transition to an oversight role, focussing on the interfaces between systems in the array rather than individual systems. A senior leader will normally only get involved with the megascience project if a major crisis arises that threatens the confidence of stakeholders. The project leader will exhibit a leadership style far more in line with the literature (Gluck and Foster, 1975; Wheelwright, 1992). Having previously not been in a realistic position to exercise significant influence,[53] the newly appointed project leader has a specific mission to construct the machine system. At first the project leader acts in a supportive role, seeking to understand why things are slipping rather than intervening directly. However, as noted in Sections 4.2.5 and 5.2.7, project leaders tend to become more transactional towards the end of the project. This is identical to the observations by many authors that management devotes more time to a development project at the later stages even though they have a more limited ability to influence the outcome (Gluck and Foster, 1975; Hater and Bass, 1988; Wheelwright, 1992; Kirkpatrick and Locke, 1996; Tracey and Hinkin, 1998).

These findings also indicate that senior leaders in megascience projects act in a coordinator role above the project structure, similar to the project champion described by Vickerman (1994). As Kirkland (1995) and Genus (1997) identified the lack of a coordinating force above a consortium as an important factor in the significant cost overruns of the Channel Tunnel, the establishment of such a coordinator demonstrates accountability to stakeholders. In this particular case, the senior leader of a megascience project demonstrates accountability to national governments and the wider scientific community.

6.5 - Rival explanations of the characteristics of leaders

The findings of this thesis both provide support for the existing literature and allow for the further development of theory about leadership within megascience projects. However, I will first explore two rival explanations for the characteristics of leaders uncovered by the case studies.

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[53] While the appointed project leader will have been involved in the detailed technical discussions, given that they will be extremely technically competent, this will likely have been on a first-amongst-equals basis rather than being in a position to enforce their opinion.

6.5.1 - Did risk act as the primary determinant affecting leadership?

One alternative theory governing the leadership differences between accelerator construction and experimental collaborations concerns risk. Some literature has investigated the perception of risk by groups compared to the individuals within that group (Rabow *et al.*, 1966; Hoyt and Stoner, 1968). Such research indicates that groups tend to take greater risks with decisions compared to those taken by members of the group acting alone (Rabow *et al.*, 1966; Hoyt and Stoner, 1968). This is an alternative theory that could explain the reasons why the experimental collaborations design and fabricate virtually all components by themselves, often having to develop new processes to satisfy detector tolerances (Evans, 2009); whereas the accelerator physicists designed the magnets and then hand this design over to industry for fabrication. This alternative theory seeks to explain the reasons that the collaborations chose to pursue the risky strategy of developing their own manufacturing techniques and technical solutions while the accelerator constructors outsourced magnet fabrication to industry. The collaboration therefore bears the burden of risk internally while the accelerator constructors export the risk to external contractors. It could therefore be argued that the choice for consensus-based collaboration decisions leads to riskier decisions.

However, this ignores some of the risky decisions taken by individuals in the accelerator construction world. Firstly, Wilson's frequent choices to pursue new accelerators which maximised technical parameters at the cost of machine reliability did carry risk (Hoddeson *et al.*, 2008). Secondly, individuals involved with the CERN accelerators have occasionally taken risks. The most memorable example from my literature search was the choice by the then-Director-General in the 1970s to accept Carlo Rubbia's proposal to build a proton-antiproton collider at CERN – despite there being no guarantee that such a proposal would prove fruitful (Krige, 2001). However, CERN was willing to take the risk in exchange for the possibility of enhancing the prestige of the laboratory and 'beating' Fermilab to the discovery (Krige, 2001). As I noted in Section 5.2.9, the normally democratic experimentalists were even willing to overlook Rubbia's authoritarianism because they believed he could deliver. However, as I have noted before, Rubbia and Wilson are relatively unusual leaders because of their authoritarian characteristics. This is why I have chosen not to describe risk-taking as a characteristic of *all* leaders in megascience projects because it is an unusual behaviour.

6.5.2 - Could my observations of leadership be the result of all megascience projects being applied rather than basic science?

In Section 3.2.1, I set out my selection criteria to create a suitable pool of megascience projects to investigate by proposing three types of project – basic science, applied science and pure infrastructure. So as to avoid any 'contamination' of my sample, I chose to be discriminating and select only from those projects considered 'basic science' in nature.

However, one could argue that most megascience projects are effectively applied science in practice as it involves the application or development of new technologies to achieve certain engineering-based goals. The basic science therefore acts as an incentive to complete the applied component. While it is true that there is a significant amount of engineering involved in any megascience project, one must also bear in mind the intended use of the final piece of apparatus. To return to my applied science example from Section 3.2.1, the National Ignition Facility explores the nature of nuclear fusion with rather immediate applications in nuclear weapons design and in fusion reactor technology. By contrast, there have been no direct applications of the W and Z bosons nor from the Higgs Boson which were both discovered at CERN. While it is true that a megascience project includes a strong component of engineering during its construction, the intended scientific experiments are purely basic in nature. As an additional example, one might consider the LIGO experiment in the United States, which is intended to identify gravity waves (Anon, 2015). While its construction involved the development of new civil engineering techniques to maintain its extreme sensitivity to changes in beam coherence (Anon, 2015), I do not believe it is reasonable to argue that LIGO is applied science.

6.6 - Summary

In this chapter, I have discussed and compared the findings from the two case studies in Chapters 4 and 5. One important finding common to both case studies was that each laboratory recruited different directors with different leadership characteristics to meet the phase-specific needs of their respective projects.

Although I suggested in Chapter 2 that megascience projects appeared to exhibit the characteristics of both large and technologically uncertain projects, I have found that leadership within these megascience projects manifests itself in a manner more closely resembling that of a large project rather than as a synthesis of the two types. Organisations and leaders alike take conscious steps to reduce the level of technical uncertainty associated with accelerator projects, occasionally even making interventions to reduce the level of technical uncertainty as a means of reducing costs. However, leaders within the experimental collaborations at CERN tend to act in a similar style to leaders within technically uncertain projects. Within these experimental collaborations, the focus is both on conducting a good experiment and developing the next generation of researchers.

In terms of the first research question that this thesis sought to answer, which was “what are the characteristics of those who lead megascience projects?” the evidence obtained from the two case studies reveals that technical competence was the first key characteristic of leaders. This technical competence provided a foundation for respect. However, the deep level of technical competence could be limited only to the key technologies. At the most senior levels, it was less essential to demonstrate technical competence. Nevertheless, several senior leaders took advantage of the prestige associated with scientific awards, such as the Nobel Prize, to indicate it. The second characteristic of leaders was management ability, which was required to bring about project success. In some cases, it was possible to select senior teams to ‘fill’ particular skills gaps. This is more pronounced at higher organisational levels.

The third and fourth characteristics of leaders emerged during discussions over transformational leadership – namely a vision and charisma. A vision is particularly important for senior leaders in combination with charisma as an inspirational tool to unite the laboratory, with leaders at other organisational levels adopting this vision while demonstrating their own charisma to motivate teams to achieve goals. The fifth characteristic of leaders usually only emerged towards the end of the megascience project when the major technical issues had been resolved – behaviours associated with transactional leadership. The sixth and seventh characteristics of leaders in megascience projects, team empowerment and trustworthiness, had related components. While leaders empowered teams to determine the most appropriate methods to implement tasks, both parties required trustworthiness so that the leader could rely on the team to deliver while they could focus on other activities. This even extended to project leaders, memorably the trust given to Lyn Evans by the CERN Council that subsequently led to measures taken to retain that trust during a 2001 budget crisis.

The findings from the two case studies also helped answer the second and third research questions for this thesis which were “Where and how were their leadership skills developed?”. The primary place for leadership development was within the laboratory where the observation of future talent takes place. Following the identification of this talent, individuals develop their skills through practical experience of leadership. In some cases, classroom learning reinforces this practical leadership experience but this is not a standard process. This indicates that the scientific community perceives leadership as a response to external stimuli, but one that still requires an individual or organisation to cultivate leadership potential. The idea that becoming a leader is a process that requires experience also exists at the most senior levels where, following the nomination of a new Director-General at CERN, there is a transitional year. During this time, the new appointee shadows the current Director-General to gain experience of their future role. The *where* and *how* regarding leadership development in megascience projects is mainly within the laboratory using practical experience.

One leadership issue that emerged during the fieldwork was the apparent contradiction between perceptions and observations of transactional leadership - namely, that transactional leadership was widely seen as inappropriate for managing scientists but was nevertheless deemed to be acceptable at the end stages of a megascience project. Through discussion with the interviewees, I concluded that there is a significant difference between ‘normal’ scientific work, where there are many ambiguities, and a megascience project, where there is an early drive to minimise technological uncertainty. The settlement of technological issues at an early stage then allows the leadership to manage a megascience project in a similar manner to other large projects. This includes the introduction of a more transactional leadership style.

A second leadership issue that emerged from the two case studies was that of the role of democratic leadership. The scientific community cherishes the ideal of consensus-driven decision-making but this is not always possible. This introduced a problem - while the community regarded democracy as a good concept, unchecked democracy could lead to substantial issues. The primary question was how to manage these issues. The accelerator construction projects such as the LHC and Tevatron sidestepped this issue by centralising resources and fixing the accelerator design at an early stage. This allowed the project management teams to control the project and minimise disputes as the technologies were already decided. ‘Democracy going too far’ was a frequent issue for experimental collaborations, a challenging situation because the collaborators control a significant proportion of the resources. To combat this, the collaborations have introduced an element of 'guided democracy' whereby some leaders allow open debate but are able to limit the choices and thus prevent radical change.

A final issue related to authoritarian leadership, where there was also an apparent gulf between attitudes and reality. The interviewees argued strongly against authoritarian leadership within megascience projects because it was seen as demeaning to scientists. Yet there were several examples of successful authoritarian leadership both within megascience projects and elsewhere within science. Upon examining these findings in relation to the pre-existing literature, I observed that authoritarian leaders tend to rise to prominence during periods of crisis at a laboratory. The definition of a crisis can vary from a traditional crisis to ones unique to science such as a lack of awards or discoveries. In these situations, the scientific community, including highly democratic experimental collaborations, may be willing to relinquish at least temporarily its traditional autonomy to a strong leader who can take the necessary measures to ensure future success. It is such an example of authoritarian leadership that led to Krige's (2001) development of the concept of the heterogeneous engineer. As discussed in Section 6.2.5, this indicates that scientists react to authoritarian leadership in much the same way as other high tech workers.

A significant finding of this thesis relates to the existence of four project phases, which offered the opportunity to tailor the recruitment strategy when selecting senior leaders. Each senior leader worked to achieve the medium-term goals of the organisation before a replacement took over to enable the next phase. While this phenomenon was less clear at Fermilab than at CERN, the directors over the lifetime of the Tevatron programme nevertheless demonstrated similar effects. Notably, although Lederman did not resign to allow a new director to take change of the construction of the Tevatron, he still responded to the change in phase by delegating significant autonomy to three appointed project managers. I examined this phenomenon using contingency theory, which classifies leaders and situations to allow a matching process to take place. Through analysis, I proposed four different project phases - initiation, approval, construction, and exploitation. I also mapped these phases against the phases observed in other types of project lifecycle and concluded that a large project's life cycle fits the standard project life cycle model rather better than either the Wheelwright (1992) or the Gluck and Foster (1975) models considered in Table 2 in Section 2.3.5.

Chapter 7 - Conclusions

This thesis is an analysis of leadership in megascience projects. The findings from the Tevatron and the LHC case studies reported in Chapters 4 and 5 respectively point to various new theoretical implications considered in Chapter 6. This chapter, Chapter 7, summarises the findings of this thesis and discusses the resulting policy options. Section 7.1 briefly describes the main conclusions and indicates the main contributions that this thesis makes to the literature. Section 7.2 discusses the policy implications of the findings. Section 7.3 considers the limitations of the study and examines what future research is needed to address and overcome these limitations. Finally, Section 7.4summarises the chapter and the thesis.

7.1 - Thesis contributions

In Chapter 2, I considered those aspects which relate the leadership and project management literature relating to this research. The literature suggests that megascience projects possess characteristics typical both of large projects and also of technically uncertain projects. However, my findings do not support this, rather suggesting a different situation, in which leaders within the two megascience projects examined in this thesis take deliberate steps to minimise the level of technical uncertainty, including interventions by senior leaders to choose technologies and thereby control costs and/or manage schedule overruns.

This thesis contributes to the leadership literature by identifying the leadership characteristics of those who lead megascience projects. These characteristics include technical competence as a foundation for respect, management ability to implement change, trustworthiness that a leader can deliver, a vision for a senior leader to inspire an entire laboratory, charisma so that other leaders can unite teams, transactional characteristics to complete a project, empowering a team, and the role of guided democracy (Table 6 in Section 6.2.8 presents a full summary of the characteristics of leaders in megascience projects).

I have also shown that the heterogeneous engineer concept is based on something of an anomaly within megascience projects. While Krige (2001) first applied the concept to a single individual, other authors have previously stated that an individual could be a heterogeneous engineer (Hughes, 1987; Law, 1987b). It is therefore inappropriate to attempt to use that concept as the basis on which to build a more general leadership theory. This unexpected finding represents an additional contribution to theory.

Within this thesis I have identified differences in characteristics, apparent when comparing leaders of accelerator construction projects and those of experimental collaborations. In accelerator construction projects, the endeavour is organised in the manner of a traditional large project, as characterised by Flyvbjerg *et al.* (2003), and steps are taken to define as many of the systems as possible to reduce the level of technological uncertainty in the early stages. However, experimental collaboration projects tend to be structured in a less traditional manner, primarily due to fundamental differences in the funding arrangements. Whilst accelerator projects are centrally resourced, the experimental collaborators hold the resources locally with spokespersons forced to convince these collaborators (and through them, their funding sources) to provide the necessary support. Members of these experimental collaborations described the ideal decision as one made by consensus, although certain mechanisms have been developed to reduce the range of choices to those deemed acceptable by spokespersons. Many interviewees described this mechanism as a form of ‘guided democracy’.

A contribution of this thesis to the project management literature has been the identification that the selection of different leaders is to some extent tailored to suit a particular project phase. Each leader is selected at least in part to enable this particular phase to be completed successfully before replacement by a new leader for the next phase, although there was no archival material to indicate that this was a conscious strategy. This strategy, implemented by both Fermilab and CERN, has proved highly effective because it has allowed for continuity of vision while also tailoring leadership to the stage-specific needs of the project. Through analysis, I detected four distinct phases in the lifecycle of a megascience project – initiation, approval, construction, and exploitation. The mechanism for changing the leader can vary depending on the specific circumstances pertaining to the particular laboratory. However, those laboratories that created internal triggers for leadership changes seem to relate better to stakeholders than those laboratories where external stakeholders or circumstances have triggered changes in leadership. An additional contribution to the literature relates to this finding and the project lifecycle. I found that senior megascience project leaders give extensive attention to detailed technical decisions during the early stages of the project and then gradually disengage during the life cycle to provide oversight. This is in apparent conflict with the literature that indicates that the reverse is normally true, namely that management tends to offer significant leeway at early project stages and exercises greater influence at project end stages (Gluck and Foster, 1975; Wheelwright, 1992). On balance, this is a reflection of the need for technical competency at all project levels. In most development and large projects, the organisation or client may lack technically competent senior leaders so they will generally defer to experts elsewhere such as the delivery partner (Flyvbjerg *et al.*, 2003; Davies and Mackenzie, 2014; Flyvbjerg, 2014; Davies, 2017). If this happens, the client usually emphasises flexibility and the creation of abroad brief to allow the delivery partner the ability to define the system (Lenfle and Loch, 2010; Davies and Mackenzie, 2014). However, when that expertise is available in-house or can be rapidly brought into the client structure, it is possible to define many more aspects of the system at an early stage with a lower likelihood of subsequent amendment.

7.2 - Options for policy practitioners

The findings from this thesis, besides providing various contributions to knowledge, also have policy and strategic implications for large laboratories. As discussed in Section 6.2.5, the finding that leaders in megascience projects share similar characteristics to those from the high tech and engineering industries indicates that it may be possible to extrapolate these findings to other situations. Below, I discuss the policy options for major scientific facilities offered by my thesis.

7.2.1 - Options for major scientific facilities

1) With regard to the training of future leaders, both the experimental collaborations and accelerator construction projects rely heavily on the informal identification of future leaders. Such a process, however, may be subject to unintentional bias, as an individual is most likely to identify a future leader based on the behaviours they themselves exhibited at an early career stage. Laboratories therefore have the option to introduce a brief training on the identification of future leaders that seeks to expand the understanding of early leadership behaviours. This could be incorporated into pre-existing training programmes. This training course would seek to systematise the process of identification of future leaders. However, it comes with the risk that by standardising the search process, it may become limited to *only* those characteristics mentioned in the training course. This could exclude the detection of advantageous anomalies such as individuals behaving as a heterogeneous engineer.

2) A second policy option is for laboratories to institute formal terms that limit how long a senior leader can serve in their position. Given the finding in Section 6.4 that the laboratories investigated chose to tailor the selection of senior leaders to meet phase-specific needs of the project, it could be useful to adopt a similar policy across other types of laboratory. The formal institution of such a policy would allow the introduction of standardised criteria and selection panels formed on a proactive cycle rather than in response to unexpected external events.

   One potential advantage of such a policy would be that laboratories could establish uniform procedures. For example, the creation of a fixed timetable for the recruitment, selection, and training of senior leaders would introduce greater certainty to the process. All parties would then understand when the process for selecting a new leader would occur and selection panels could scan more extensively for potential candidates. This would put the laboratory in a stronger position during the recruitment and selection process

   A disadvantage of introducing this policy might be that the talent pool for senior laboratory leaders might be reduced to those leaders who easily fit into the four phases. The intention of this policy is to help laboratories approaching the progression to the next phase of a major project to categorise potential candidates in order to establish a matching process using contingency theory, which I discussed in Section 6.4.1. It is certainly not intended to reduce the pool to *only* those within the four categories, and those responsible for implementation should be aware of this and take steps to avoid it.
3) One particular opportunity relates to the structural relationship between a laboratory and its stakeholders. As identified in Appendix 1 and Section 4.4, Fermilab has had a difficult and occasionally turbulent relationship with the US government whenever the two parties have had divergent goals. In these situations, Fermilab has been forced to negotiate for several years before the release of funding. Fermilab is in a weaker position than CERN, because it is primarily dependent upon a single source of funding. As the focus of Fermilab is moving away from proton-proton collisions towards becoming a neutrino physics laboratory, its relationship with CERN is no longer the "competitive collaboration" that Lederman (1983) described in the 1980s. This provides Fermilab with an opportunity to re-structure itself as a 'CERN of

neutrino physics' by becoming a treaty organisation and formally separating from the US national laboratory system. As I observed in Section 4.4, the damage caused by Wilson's resignation significantly affects the internal culture to this day. By re-structuring and diversifying its funding sources, Fermilab could manage and overcome a substantial weakness in its relationship with the US government.

7.3 - Limitations and potential future research opportunities

Section 6.5 considered possible alternative explanations for my observations of leadership in megascience projects. Nonetheless, there are certain limitations to this research, and acknowledgement of these limitations creates some exciting new research opportunities.

7.3.1 - Wider applicability

An obvious question arising from this thesis is the feasibility of extrapolating the findings to other projects since, as noted in Section 3.2.2, megascience projects are large in size although few in number. Although I made a deliberate decision in Section 3.2.1 to investigate two distinct but related projects to determine what is unique to one megascience project and what is common to all megascience projects, one might argue that those two projects still constitute an unreliable foundation for developing new theory (Yin, 1994; Stake, 2005). However, I would argue that the importance of studying megascience projects lies in their size rather than their numbers. The size of these projects means that, although few in number, they can have a substantial financial impact on government budgets.

There is considerable interest in megascience projects both from policy-makers and the general public, with the LHC in particular being the subject of many popular science articles (Aron, 2015). Therefore, while these two projects might be considered unusual because of their size, it is still worthwhile to document these cases. As I noted in Section 3.1.1, case studies seek to report the nature of a phenomenon (Stake, 2005). There is a significant degree of technological overlap (Hoddeson, 1987; Hoddeson *et al.*, 2008; Collins and Evans, 2009). Additionally, these projects are good examples of megascience projects in general. Although some authors have borrowed the term 'big science' to refer to other projects, they have frequently lacked a single consolidated site at which most if not all of the experimentation takes place (Collins *et al.*, 1998).

One important scientific project falling into this category is the Human Genome Project (HGP). Because it was possible for experimentation to take place at most collaborating institutions, there was no need for a consolidated site, therefore effort could be distributed across all partners (Collins *et al.*, 1998). By contrast, in particle physics and space science, the collaborators tend to pool their resources into a single design (Shore and Cross, 2004; McCray, 2010; Evans, 2014), which confirms that the Tevatron and the LHC, with their single consolidated sites, represent good examples of megascience projects. Nonetheless, this issue presents the opportunity to expand the research to other particle physics laboratories. An expansion of the selection criteria to include somewhat smaller projects would have allowed the inclusion of accelerators constructed not just in Europe and the United States but also elsewhere in the world. By investigating additional projects, such as other candidate projects that I identified in Section 3.2.2, I could determine whether this question mark over the generalisability of my findings was justified.

7.3.2 - Time intervals between the project and my research

This thesis investigated two megascience projects – the Tevatron at Fermilab in the USA and the LHC at CERN in the Franco-Swiss border region. While the LHC was completed relatively recently in 2008, the Tevatron construction occurred much earlier. In some cases, interviewees were asked about decisions that had been taken over 30 years ago, which will have inevitably affected the accuracy of the data to some extent. These decisions may have been disputed and the interviewees may have justified their decision based on *post-facto* events. Other interviewees may have had negative experiences with leaders who have become incapacitated or died during the intervening years with the result that they did not wish to divulge the true story out of respect for their former colleague. While it was possible to use third party accounts of the most senior leaders to triangulate interviewee comments, such documents were never produced for leaders lower down the organisational structure.

While the ideal plan for this research would have been to investigate two currently running megascience projects, this was not possible. As the scientific community tends to develop only one or two big accelerators each decade, temporally coincident projects will inevitably be a rarity. Now that particle physics has developed to a point where projects are so large that each accelerator is expected to have an operating life measured in decades, it will only become more challenging to find two projects in the same phase at the same time.

7.3.3 - The projects as an extension of national cultures

The majority of projects that would qualify as megascience projects according to the definition set out in Section 2.4.1 are located in western countries. Therefore, it could be argued that the decision taken in Section 3.2.2 to focus primarily on megascience projects in western countries introduced a systematic bias in leadership toward styles appropriate for westerners. This might seem a reasonable argument, but it ignores the reality that while the projects may be physically located in western countries, the community served by such projects is global. Although national culture does not seem to be a significant impediment to the creation of scientific collaborations, I still have the opportunity to further demonstrate this point by extending the study in future to include non-western laboratories. Fortunately there are currently initiatives toward developing new scientific institutions in non-western countries such as SESAME in Jordan (Khan, 2002; Einfeld *et al.*, 2004). Although there are currently no projects that meet my original megascience definition, this may change at some point in the future.

Now that this research into megascience projects within particle physics has been completed, I have the opportunity to apply my methodology to another field of science. The first option could be space science, which emerged as a potential area of study in Section 3.2.2 but where concerns over access were seen as a potential problem. If it is possible to convince the appropriate gatekeepers to grant access to the materials, it might even be possible to compare large-scale national, international and private consortia given the recent private sector space initiatives (Musk, 2009).

7.4 - Summary

This thesis has sought to examine the nature of leadership within megascience projects. The research reveals that leaders within megascience projects exhibit characteristics that include technical competence, management ability, and trustworthiness. The findings also indicate where and how leaders develop their leadership skills within megascience projects. This is within a laboratory framework that gives future leaders practical experience but with the additional possibility of classroom learning to reinforce those experiences. This indicates that scientists within megascience projects view leadership as a characteristic that requires development more through experience rather than classroom training alone. I have contributed to the leadership literature in this thesis by identifying the leadership characteristics in a novel setting and determining that leadership in megascience projects is similar to that found in other high tech or engineering projects.

The thesis also contributes to the project management literature through an unexpected finding that emerged during the fieldwork - laboratories pursued a policy of tailoring the selection of senior leaders to meet the phase-specific needs of a megascience project. I analysed this in terms of contingency theory and identified four distinct phases – initiation, approval, construction, and exploitation. I then compared these phases to three widely used models for the project life cycle and concluded that these phases broadly matched the traditional project life cycle model (Adams and Barnd, 1983; King, 1983). Each of these phases had different leadership requirements and committees selected a leader who could best lead the project though the next phase. The conclusion of each phase offered laboratories the opportunity to replace the senior leader with another person suited to tackling the next phase in the cycle. However, I also observed that the behaviours of the senior leader are the reverse of those that have been observed elsewhere in the literature (Gluck and Foster, 1975; Wheelwright, 1992).

8 - References

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Appendix 1 –Brief histories of the Tevatron and the LHC

This appendix discusses the historic context of the two megascience projects used as case studies for this thesis, namely the Tevatron at Fermilab and the LHC at CERN. This appendix is composed of three sections. Section A1.2 comprises a brief introduction to the appendix. Sections A1.3 and A1.4 inform the historic events related to the Tevatron and the LHC respectively. Within this appendix, I also suggest sources that a reader may refer to for additional information.

A1.1 - The Tevatron at Fermilab

This section comprises a description of the key events that occurred at Fermilab during the life of the Tevatron. It provides information concerning the reasons underlying certain decisions.

A1.1.1 - The creation of Fermilab

As discussed in Section 1.1.1, after the Second World War the US government provided substantial funding to science, giving rise to terms such as ‘Big Science’. Many of the prominent scientists associated with the Manhattan Project, the American atomic bomb project, originally came from a nuclear physics background. Their previous expertise and their utility to the Manhattan Project resulted in the US government granting physicists significant resources; the field retained an association with national security.[54] As a result, the US National Laboratory system emerged, and many of these laboratories studied technologies with military applications (Galison and Hevly, 1992). As these new technologies emerged, it also became possible to probe more deeply into atomic structure, resulting in the new findings which indicated that some subatomic particles themselves also have an underlying structure. It was from these developments that the new field of particle physics emerged as a distinct sub-field of nuclear physics. Although particle physics did not share the same immediate military applications readily offered by nuclear physics, nonetheless, because of its historic associations, it was a well-funded subject.

[54] For additional information regarding the Manhattan Project and the relationship between government and science during the Second World War, see Hughes (2002). Regarding the debate within the US government over the direction of postwar science, see Kevles (1977)

There were two primary particle physics laboratories in the US at this time – The Lawrence Radiation Laboratory[55] in Berkeley, California and Brookhaven National Laboratory in New York. However, these two laboratories practiced a form of discrimination in that only researchers affiliated with their respective universities were permitted to conduct experiments. This created a 'two tier' experimental community with those researchers not associated with the 'correct' universities having to go elsewhere. In response to this issue, a Professor at Columbia University, Leon Lederman, proposed the concept of the 'truly national laboratory' that would be open to all those who wished to conduct experiments (Lederman, 1963; Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008). Other events also led to the creation of what would become Fermilab. The first event was the collapse of MURA, a Midwestern attempt to create a rival to Brookhaven and Berkeley (Jones *et al.*, 2010).[56] The second event related to attempts to build a 300GeV machine. As briefly described in Section 4.1, Berkeley and Brookhaven competed for the right to host this machine (Hoddeson *et al.*, 2008). Berkeley won the competition but was unable to follow through on its ambition to meet the design specification within budget constraints.

Robert Wilson, a professor at Cornell University, criticised the subsequent proposed design as being overly conservative and too expensive and proposed an alternative design in 1965 that was significantly cheaper. Unfortunately this design was regarded by Berkeley as a threat to its traditional dominance of particle physics rather than advice. The consortium created to build and manage this new facility, URA, proposed a competition to select the accelerator site to draw the particle physics community back together after the Berkeley-Brookhaven competition. The site selection competition also offered the opportunity to break the coastal dominance of the field. Eight sites offered themselves for consideration, three in the Midwest and five others widely distributed across the US. The Midwestern sites had the advantage of accessibility from their central locations and a pre-existing particle physics community from the MURA initiative (Hoddeson *et al.*, 2008; Jones *et al.*, 2010). Despite some notable civil rights issues, URA

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[55] After the death of Ernest Lawrence in 1958, the Radiation Laboratory of the University of California, Berkeley incorporated the name of its founder before undergoing subsequent name changes during the 20th Century.

[56] Jones (2009) wrote an extensive account of MURA

selected the Illinois site as the location of the new laboratory in 1966.[57] During this time, Wilson had returned to Cornell to lead the construction of an electron synchrotron, which was completed on budget and on time. This success marked him out as a candidate for the directorship of this new laboratory. After a challenging appropriations process, the necessary US$250 million was allocated to the accelerator. Wilson used this as an opportunity to build his ideal laboratory, which melded the old western and the new scientific frontiers. Native flora and fauna were re-introduced to the site, including a herd of bison. The laboratory also incorporated pre-existing structures into storage facilities, merging the traditional and the modern. This synthesis of the old American west and modern science was Wilson's vision for the laboratory. Even today, it still has a significant power over those who work at Fermilab. The 'Main Ring' was the first accelerator at Fermilab, but even during its construction superconductivity offered the theoretical possibility to increase its maximum energy. However, it was several years before technical advances made superconductivity an applicable possibility.

A1.1.2 - Conception of the Tevatron

The Tevatron was designed to take Fermilab to the 'energy frontier' by upgrading the conventional magnets used in the Main Ring with superconducting magnet technology. The idea was conceived early in the life of the laboratory, its first public announcement being before the US Congress in 1977 under the name 'Energy Doubler' (Hoddeson *et al.*, 2008). This new accelerator offered the possibility of reducing Fermilab's running costs while retaining American leadership in particle physics (Hoddeson *et al.*, 2008). Fermilab management took a conscious decision to leave space during the construction of the original Main Ring accelerator for such a future superconducting machine (Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008). The Tevatron underwent a series of name changes, firstly as the "energy doubler", then the "energy saver", before settling on naming the new facility the "Tevatron". The new superconducting magnet technology, although requiring a higher initial investment, would have significantly lower running costs (Hoddeson, 1987; Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008; Evans, 2009). Fermilab intended to use the Tevatron at a record-breaking energy by constructing a new

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[57] For additional information regarding the early years of URA and the site competition, please consult 'The Early History of URA and Fermilab' by Norman F. Ramsey, part of the Fermilab Golden Books collection.

ring of superconducting magnets below the pre-existing Main Ring[58] and constructing associated infrastructure which would enable proton-antiproton collisions.[59] The new superconducting magnet technology, although requiring a higher initial investment, would reduce power consumption by a third (Hoddeson, 1987; Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008). During the early life of the laboratory, although there were no specific appropriations, the existing budget could fund superconducting magnet research. Hoddeson *et al.* (2008) describe Wilson as taking an active role in the R&D process, setting up groups to investigate technical options and allegedly dominating discussions and decisions. Wilson's primary contribution was recognition of the need for internal superconducting wire production lines to satisfy the precise requirements of the Tevatron, as several interviewees also noted. A vast operation was set up to construct and test the wires and later the assembled magnets in a way that would be replicated in future synchrotron projects. Experiments took place using smaller scale magnets as a cost saving move with successful characteristics incorporated into larger prototypes (Hoddeson *et al.*, 2008; Evans, 2009; Rogalla and Kes, 2011).

A1.1.3 - Obtaining government approval for the Tevatron

Gaining approval for an undertaking such as the Tevatron required consent from the US federal government; a common tactic, previously used by scientists, had been to justify additional investment by appealing to patriotism (Hoddeson *et al.*, 2008). Although the particle physics community is composed of itinerant scientists, accelerator construction projects frequently secure funding through the exploitation of national pride such as the SSC (Smith, 2007; Hoddeson *et al.*, 2008; Riordan *et al.*, 2015). However, the transition of the Tevatron from the R&D and design phase to construction coincided with a rationalisation of US energy policy and a change in public perception of science (Issawi, 1978). After a short period under the purview of the Energy Research and Development

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[58] The Main Ring, the first Fermilab accelerator, originally reached 200GeV beam energies but later upgrades increased that to 400GeV by the time that Tevatron construction began. As part of the Tevatron programme, the Main Ring received minor upgrades to act as an injector at a lower energy of 125GeV. During the 1990s, the laboratory moved the Main Ring into a new tunnel and renamed it the 'Main Ring Injector' in acknowledgement of its new role.

[59] Superconducting magnets utilise a cryogenic system at extremely low temperatures[59] to reduce the resistance of a magnetic wire to almost zero (Hoddeson, 1987; Rossi, 2010; Evans, 2014). A near-zero This stronger magnetic field exerts a more powerful Lorentz force on moving charged particles, sustaining a more energetic particle beam in the beam pipe until other factors become the primary limitation (Evans, 2009). A lower resistance allows higher current through the magnetic wire at equivalent voltages, creating a stronger magnetic field at low running cost (Evans, 2009).

Administration, the creation of the Department of Energy[60] stabilised the management of Fermilab (Hoddeson *et al.*, 2008). The DOE took a more interventionist approach compared to the former Atomic Energy Commission, which had administered Fermilab for most of its life. Under the Atomic Energy Commission, little effort was expended to learn from experiments with project management tools, notably when the Lawrence Berkeley Laboratory implemented critical path management schemes (Hoddeson, 1992; Galison, 1997). Unfortunately, during the latter part of the 1970s, public sector budgets came under sustained pressure (Issawi, 1978). This forced government projects to incorporate project-tracking tools to demonstrate greater accountability (Hoddeson *et al.*, 2008). DOE wished to amalgamate best practices across the national laboratory system. Senior figures at Fermilab were unhappy at what they perceived as an intrusion into science (Hoddeson *et al.*, 2008). In reality, Fermilab was put on an equal footing with other areas of the government budget, whereas previously the Atomic Energy Commission had received a dedicated budget and allocated a significant proportion directly to the laboratories to manage themselves. Additional project funding was granted purely on scientific merit, as many employees were drawn from the scientific community (Seaborg and Seaborg, 2001). There was an upheaval in the laboratory structure with the introduction of this new governance, partly due to Wilson's resignation in protest over the funding situation (Anon, 1978; Glanz, 2000; Staley, 2004). Wilson had hoped that the mere threat of resignation would secure the important Tevatron funding to allow the programme to move from R&D to construction, but when the financial year 1978 US federal budget was unveiled, there were no Tevatron-specific appropriations (Hoddeson *et al.*, 2008). Wilson then felt that he had no choice but to carry out his threat, and so submitted his resignation to the Fermilab trustees (Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008). This triggered a search for a new Director.

Leon Lederman received the offer to become the second Fermilab director in October 1978 (Hoddeson and Kolb, 2003; Hoddeson *et al.*, 2008).[61] Lederman, then a prominent member of the Fermilab experimental community, was open to working within the DOE's cost-conscious framework and welcomed the DOE offer that coincided with his appointment to build a superconducting test sector of beamline. This offer came with the

[60] Generally referred to both internally and externally by the acronym DOE.
[61] Hoddeson and Kolb (2003) have written a paper on the specific subject of the transition from Wilson to Lederman.

possibility of further development on an *ad hoc* basis under which additional funding would be released as milestones were met (Hoddeson *et al.*, 2008). This was an unstable funding situation and securing sufficient investment to turn a single test sector into an entire complex in an environment of reduced budgets would prove a great challenge.

At this time, CERN, which had a relationship with Fermilab described by Lederman (1983) as “collaborative competition”, had commissioned a new proton-proton collider enabling collisions at 400GeV. There were expectations during this period that CERN planned to upgrade this accelerator, named the SPS, to enable proton-antiproton collisions in the 540GeV range (CERN Proton-Antiproton Project, 1981; Lederman, 1983). The scientific community had hopes that this new energy might allow them to determine the existence of the quanta of the weak nuclear force known as the W and Z bosons (Hoddeson *et al.*, 2008). There was debate at Fermilab over whether they should contribute to the race by constructing a ‘satisficing’[62] accelerator, building a more powerful teraelectronvolt accelerator, or pursue an entirely different strategy. Lederman realised the importance of unity in the laboratory and organised a set-piece event to resolve this debate in November 1978, described by the literature and several of my interviewees as a ‘shootout’ (Hoddeson *et al.*, 2008). Several working groups investigated the feasibility of the various options and presented their findings at this event. One group strongly asserted that trying to ‘brute-force’ the Main Ring into a satisficing collider would require a substantial redesign which precluded being part of the W and Z hunt (Hoddeson *et al.*, 2008). Lederman reserved the sole right to decide, and cited this extensive redesign as the key factor governing his decision to allow CERN to solely answer the W and Z question and instead to pursue a teraelectronvolt accelerator (Fraser, 1997; Smith, 2007).

Initially, the Tevatron gained approval from DOE in October 1978 on this unusual financial basis. Fermilab later secured funding sufficient to pursue a single stage programme that allowed the near-simultaneous construction of the Energy Doubler/Saver and its associated infrastructure. Previous scientific projects, notably the Fermilab Main Ring and SPS at CERN, had begun life as a similar multi-stage process. Once permission is given to construct an accelerator, laboratory management needs to take steps to secure

[62] Satisficing is a term that identifies the point where the basic minimum objectives or specifications are met. It is a combination of satisfactory and sufficient.

finance (Hermann *et al.*, 1987a; Hermann *et al.*, 1987b; Krige, 1997; Smith, 2007; Hoddeson *et al.*, 2008).

The successful demonstration of a superconducting magnet sector quickly led to the DOE indicating in December 1978 that a single-stage programme request would be approved (Hoddeson *et al.*, 2008). The laboratory quickly drafted this request but it was felt that the battle to secure the additional funding needed a new dimension. According to Hoddeson *et al.* (2008) this front was opened by of a June 1979 New York Times editorial. In the article, Lederman depicted the potential loss of American scientific leadership to well-funded Europeans – an event which he proposed could precipitate national decline (Browne, 1979). At the centre of this race was the W boson, described as "vitally important" (Browne, 1979). It was therefore imperative for DOE to fund this new accelerator to sustain American leadership in high-energy physics and reduce electricity costs. It is difficult to determine whether the article proved to be a pivotal factor, but the single stage project received approval in July 1979.

A1.1.4 - Construction

The Tevatron programme[63] became composed of three projects, each project was officially the responsibility of the Fermilab director, Leon Lederman, who subsequently delegated each project to an appointed manager.:-

The first project was the Energy Doubler/Saver; this required the construction and installation of a superconducting ring of magnets to accelerate protons to 500GeV. This superconducting magnet synchrotron is what most physicists refer to today as the Tevatron. The project leader for the Energy Doubler/Saver was Helen Edwards, who had extensive experience in the design, construction and commissioning of accelerators (Hoddeson *et al.*, 2008; McDaniel and Silverman, 2009). Although there were a few Main Ring tunnel access issues[64], Edwards still managed to get the project completed on time although not on budget. As the Energy Doubler/Saver involved more technically

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[63] The best publically available resources concerning the progress of the projects are the various Fermilab annual reports between 1979 and 1985.

[64] Although there were few issues during the construction project, there was an extended commissioning process. The laboratory considered this an unavoidable consequence of operating at the limits of technology.

uncertain activities, specifically designing superconducting magnets for first of a kind use in particle physics, it is not a surprise that there was such an increase (Webre, 1988).

The second project was Tevatron I, which comprised the construction of the infrastructure and upgrades to allow proton-antiproton collisions. This entailed the construction of the antiproton and colliding beams infrastructure. The project leader for Tevatron I was John Peoples, Jr., who had an interesting educational background. He had originally trained in engineering before spending time working at the Martin Aircraft Corporation, an industry where project management developed. This project had a more troubled life: the original technology to maximise the luminosity of the anti-proton beam failed to operate as expected, as discussed in Section 4.2.8. This resulted in Lederman's intervention to switch to an alternative all-stochastic cooling method, only recently discovered to be a viable process (Möhl *et al.*, 1980; Hoddeson, 1987; Hoddeson *et al.*, 2008). This led to a substantial cost increase and schedule slippage, as a substantial portion of the project required re-examination from first principles.

The third project was Tevatron II, which comprised the infrastructure and upgrades for fixed target collision experimentation. The infrastructure constructed during Tevatron II allowed beam transport of various types of particle at 1TeV energies to the fixed target experimental areas. This necessitated upgrades to pre-existing beamlines to retain the beam energy all the way to the target. The project leader for Tevatron II was Tom Kirk, a scientist with significant fixed target experimental experience (Anon, 1982). The project seemingly progressed smoothly with only a marginal cost overrun at less than 0.1% of the original budget request; there were a few efficiency concerns as a substantial department re-organisational took place partway through the project.

A1.2 - The Large Hadron Collider at CERN

This section comprises a brief description of the historical context of the Large Hadron Collider at CERN near to Geneva, Switzerland. In some cases, the events described here may help to inform some of the decisions taken during Chapter 5. This section provides some of this additional information for the reader's benefit. Some of the narrative will describe a major rival to LHC also planned during this time – The Superconducting Supercollider.[65] This was an American project planned to operate at even higher energies

[65] Often referred to by the acronym SSC. Riordan *et al.* (2015) have provided a thorough account of the SSC's lifetime.

than the LHC, but a combination of cost overruns and management difficulties resulted in its cancellation in the 1990s. These same issues would become a major concern of the CERN Council during the LHC project and may well have influenced CERN management to take steps aimed at preventing a similar fate for the LHC.

A1.2.1 - The creation of CERN

Both before and after the Second World War, a number of European scientists had moved to North America to conduct their research, resulting in a facilities gap between the two continents (Hermann *et al.*, 1987a). In 1950, UNESCO proposed the creation of a pan-European laboratory to fill this gap and encourage international cooperation; one of many initiatives designed to foster European cooperation and thus help to avoid another war. For example, while this proposed laboratory intended to promote international scientific collaborations, the European Coal and Steel Community sought to integrate specific economic sectors to make a future war economically impossible (Schuman, 1950).

CERN was originally the name given to a council formed by twelve European countries to explore this laboratory option (Hermann *et al.*, 1987a). Many of the senior scientific figures who served on this council also shared the dream of a pan-European laboratory. Some had fled Europe before the Second World War, but returned to rebuild the European scientific community. Members of this council are known today as CERN's 'founding fathers'. The CERN provisional council chose to construct this new laboratory outside but close to Geneva owing to its politically neutral environment and the proposed site actually crossed the Franco-Swiss border to underline its international credentials. Despite some early proposals for CERN to distribute research sites across the continent, it has remained on a single consolidated site. This has been the source of some consternation as some member states have argued that France and Switzerland benefit from being host states but their budget contributions do not reflect this (Smith, 2007). Although the provisional council named CERN officially dissolved in 1954 and the laboratory's official French name is the *l'Organisation européenne pour la recherche nucléaire*, the acronym CERN has remained to refer to the laboratory.[66]

[66] A three volume series exists on the specific history of CERN. Volume One examines the launch and construction of the laboratory. Volume Two looks at CERN's first 20 years of operation. Volume Three looks at the following 10 years of experimentation and brings the reader to the late 1970s.

During its 60-year history, CERN has constructed a wide variety of accelerators. These have included the original Proton Synchrotron in the late 1950s, the ‘Super Proton Synchrotron’ (SPS) in the mid-1970s and the ‘Large Electron-Positron Collider’ (LEP) in the 1980s. CERN has incorporated previous accelerators into the supporting infrastructure of the next big machine.[67] The construction of LEP necessitated the excavation of a tunnel 27km in circumference; this useful asset offered the possibility that it could be re-used in a future accelerator.

A1.2.2 - Conception of the LHC

Even during the early 1980s, during the construction of the Large Electron-Positron Collider, the previous big project at CERN, a debate had begun regarding what the next big machine should be (Smith, 2007).[68] A key concern was to differentiate CERN to stay competitive and attractive to external collaborators by reaching the TeV energy range, which Fermilab had recently accomplished with the Tevatron. The Tevatron could reach the TeV range but only when colliding protons and antiprotons; this produced clean signals but the machine had issues with maintaining beam luminosity and rapidly producing the antiprotons. An alternative pathway to reaching TeV physics was to collide two proton beams. Although this was more technically challenging, it removed these luminosity and antiproton production problems. Opinion at CERN quickly converged on such a proton-proton collider installed above LEP, described as a large hadron collider. This could allow new types of experimentation by using LEP and this large hadron collider together while retaining the ability to investigate hadron-hadron and lepton-lepton collisions. These early discussions suggested using such a machine to hunt for the theorised Higgs particle. This large hadron collider concept described in 1984 underwent minor design changes before becoming the basis of the LHC. One notable change was the removal of LEP from the design on space and cost reasons. The proposed LHC would utilise superconducting magnet technology on a very large scale. This required the production of seven kilometres of magnets, each cryogenically cooled to superfluid helium temperatures of 2.4K using a single cryostat for both rings (Evans, 2009; Evans, 2014).

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[67] This is achieved by ‘daisy chaining’ the accelerators into a linear series of loops. A bunch of particles injected into one accelerator is accelerated to its maximum energy before being injected into the next accelerator in the series until the particle “bunch” attains the required energy.

[68] The Large Electron-Positron Collider is also known by the acronym ‘LEP’.

However, the LHC was not the only hadron-hadron collider planned during the late 1980s. The American particle physics community was planning a Superconducting Supercollider to be built in Texas to operate at significantly higher collision energies of 40TeV, more than twice the energy possible in the LEP tunnel (Smith, 2007; Riordan *et al.*, 2015). The SSC proposed to build the new facility in the Dallas-Fort Worth area, a place with no pre-existing particle physics laboratory. While Fermilab and CERN could use older accelerators as injectors for the next machine in the daisy chaining process, the SSC would require the construction of costly injectors at the same time. It was nonetheless widely feared in Europe that scientists would take their experiments to the US rather than CERN. There were instances of European policymakers questioning the merit of the LHC when the SSC would be a 'better' machine. Documentation and subsequent articles from CERN noted these American proposals as a serious threat to the business viability of the LHC (Fraser, 1997). CERN management, led by Director-General Carlo Rubbia, responded that while the SSC would have a higher energy, this was a superficial argument which ignored the luminosity of the LHC. The proposed LHC, although having lower beam energy than the SSC, would have a significantly higher luminosity and therefore a greater chance of collisions between particles at full energy. This enabled similar experimentation but at one fifth of the cost compared to the SSC (Riordan *et al.*, 2015). Furthermore, while the SSC would only support proton-proton collisions, the proposed LHC offered nor only proton-proton collisions, but also proton and lead nuclei collisions, and lead-lead collisions (Riordan *et al.*, 2015). The SSC suffered from vast cost overruns over its short life from an original cost estimate of US$4.4billion in 1987 to over US$18billion by 1993, possibly because of the issues noted above (Riordan *et al.*, 2015).

A1.2.3 - Securing LHC approval

The process of gaining approval for a CERN-based accelerator was more intricate than that described in Section A1.1.3 for American accelerators. The US National Laboratory system generally makes use of a single funding source, the US government. However, due to its requirement to work with multiple member states and therefore with a multiplicity of funding agencies, CERN requires approval from the CERN Council. This is a body made up of scientifically respected representatives and it is officially the supreme decision-making body of CERN. It is responsible for setting strategic goals, approving budgets, and selecting CERN management (Hermann *et al.*, 1987a; Hermann *et al.*, 1987b; Krige, 1997; Smith, 2007). The Council normally makes decisions with a simple majority but it is clearly desirable to reach consensus, especially on a massive undertaking such as the LHC. The CERN Council formally meets twice a year and each formal meeting is comprised of an open and a closed session. This gives the Council a public meeting to make decisions as well as a private meeting where Council-members can engage in frank discussions. Some decisions require a ‘double majority’ in which member states representing 51% of contributions must support the motion. The Council quickly understood the scientific merit of a large hadron collider as the fastest and cheapest way of achieving physics at the teraelectronvolt scale and passed a resolution approving the idea in principle in December 1991 (Smith, 2007).

A1.2.3.1 - Special host contributions

As noted above, a long-standing complaint throughout the history of CERN has been that the economies of France and Switzerland, where CERN is located, benefit disproportionately by hosting the laboratory, yet their budgetary contributions do not reflect this fact (Hermann *et al.*, 1987b; Smith, 2007). Previous attempts to correct for this alleged inequity have included developing a second CERN site, but ultimately the efficiencies of consolidation rendered this unfeasible (Hermann *et al.*, 1987b).[69] This issue re-emerged in 1994 when Germany and the UK wished to cut their contributions in real terms. Llewellyn-Smith moved to negotiate a special member state contribution from the host states, whereby their contribution to the CERN budget would increase while the remaining member states froze their contributions. This effectively maintained the Franco-Swiss contribution in real terms while other member state contributions fell.

Obtaining the initial approval for LHC in an environment of reduced budgets proved to be a great challenge for CERN management, but this was resolved in a similar fashion to that for a previous accelerator, the SPS, namely by gaining approval for a two-stage project (Adams, 1971). This two-stage project proposal envisaged an initial operations in 2004 with only two thirds of the magnets installed, operating at two thirds of the peak energy (9 TeV), with a later upgrade to install the remaining magnets to enable full energy collisions at 14 TeV in 2008. This acquired the title ‘the missing magnet machine’. There is some debate over whether this missing magnet machine would have been technically feasible or simply would have acted to ‘focus minds’ (Fraser, 1997). The proposed final

[69] With the additional need to construct an entire infrastructure for the accelerators, similar to the SSC described above.

cost of the first stage would have been lower but would require additional administrative costs for the second stage, with a questionable net saving relative to a single-stage project (Smith, 2007). However, the possibility of lower annual contributions seemed more palatable to member states, who subsequently approved the two-stage LHC in December 1994 (Evans, 2009). The wisdom of a two-stage project was not lost on the Council, who agreed to review the two-stage project at a later point if CERN management could acquire additional funds to bridge the funding gap. However, final approval for construction required management to acquire sufficient funding to realise the idea. Llewellyn-Smith pursued several solutions to bridge the funding gap needed to make the LHC a single-stage project even as member states cut their contributions.

A combination of national and international agendas made securing full approval a difficult exercise for the new Director-General, Christopher Llewellyn-Smith.[70] Germany and Britain in particular, for domestic political reasons, went to great lengths to enforce fiscal discipline upon the project, even threatening to pull out of CERN at one point (Smith, 2007). The double majority rule described above gave these two countries disproportionate power because of their large contributions to the CERN budget. At the European level, there was a reduction in national budgets associated with the end of the Cold War as Governments wished to reap the ‘peace dividend’ – so-called because the fall of the Soviet Union allowed for cuts in defence budgets (Fraser, 1997). Furthermore, new fiscal controls were implemented in the Maastricht treaty officially limiting budget deficits to 3% of GDP, officially making it difficult for states who were members of both CERN and the European Union to fund budget deficits.

A1.2.3.2 - Observer status

The first action taken was to extend the use of a rarely used category of CERN membership, observer status. Observer states could observe CERN Council meetings and contribute financially in exchange for scientific access (Fraser, 1997; Smith, 2007; Evans, 2009). Until the 1990s observer status was extended only occasionally to countries unsuitable for full membership at that time. However, there was a genuine need to diversify funding streams to secure the future of the project so this status was extended to many more countries. The first country offered observer status under this new policy was

[70] Smith (2007) wrote a personal account of his experiences as Director-General at CERN during this time and this offers a useful resource for the curious reader.

Japan, followed by the three other countries during 1996 (Smith, 2007; Evans, 2009). The US joined as an observer state after the collapse of the SSC project, providing much publicity and a financial victory for CERN management. Observer status suited both parties as it gave American researchers LHC access and CERN Council representation in exchange for budget contributions. This further improved the financial credibility of CERN management following a DOE review, conducted during this American assessment of LHC, which concluded that the proposed budget costings were “adequate and reasonable” (Evans, 2009; Evans, 2014). A more cynical interpretation might be that getting as many countries as possible involved with funding the LHC made it far harder for the CERN Council to cancel the project.

A1.2.3.3 - Private loans

In June 1996, while CERN management was seeking additional contributions, the German government announced that it required further cuts to its CERN contributions due to difficulties in its national reunification process (Smith, 2007). The desired reduction was of the order of 8% and this desire again soon spread to the British. Unfortunately, the previous December 1994 approval incorporated a 1% real terms reduction in all non-host state contributions. It would prove extremely challenging to build the LHC with such substantial reductions, forcing CERN to cut all contingency from the project. There was no other way to finance the project without taking out loans, something acknowledged by the German delegation despite a historic suspicion towards debt-funded investment (Evans, 2009; Evans, 2014). With these two additional undertakings to bridge the funding gap, the project was approved as a single-stage project in December 1997 (Smith, 2007).

A1.2.4 - LHC construction

The construction of the LHC required civil engineering and equipment installation by external contractors. The civil engineering rather than the installation proved the more challenging part of the project. Although CERN intended to assemble the LHC in the pre-existing LEP tunnel, certain additional work was required to enlarge existing caverns and connect the LEP tunnel to SPS to allow its use as an LHC injector. Two complications arose during the civil engineering that delayed its completion. The first was the discovery of an ancient Roman site that forced work to stop for archaeological excavation (Evans, 2014). Although unexpected, it was merely an inconvenience rather than a major technical issue. The second complication occurred during the excavation of the CMS cavern. Although early pilot shafts indicated a high level of ground water, the subsequent excavation revealed an underground river at the proposed site. Initially the civil engineers partially froze this river by pumping chilled brine to create a wall of ice three metres thick (Evans, 2014). However, this proved ineffective as the water eventually broke through into the CMS cavern (Morgan, 2009). This required the development of a more substantial solution - pumping liquid nitrogen into the cavern to freeze the river permanently, creating permafrost around the CMS shaft (Morgan, 2009; Evans, 2014). The magnet production for the LHC by external contractors consumed a significant proportion of global supply of the raw materials and even required the companies to set-up new dedicated production lines to cope with CERN's tight specifications and scales. Even then, there were issues with one supplier and the processes were internalised to prevent the issue from becoming a bottleneck.

A1.2.5 - 2001 budget crisis

At the time of the LHC single stage approval in December 1994, the CERN Council cut the laboratory budget and later permitted the project to run without any contingency reserve. As with many other large projects, cost overruns accumulated during this period and a subsequent costings review revealed a large budget gap of approximately 700 MCHF (an 18% increase from the baseline budget)[71]. Of this gap, approximately 200MCHF were from cost overruns and 500MCHF arose from incorporation of infrastructure upgrades into the project budget. Obviously, with the cancellation of the SSC because of ballooning costs, there was substantial concern from the CERN Council that the LHC might be about to fall into a similar trap. Therefore, CERN management had to take steps to ensure that the CERN Council retained their trust in management ability to keep the project running on a proposed new budget. As discussed in Section 5.2.3, trustworthiness is an important component leadership at CERN. As a demonstration of management's wish to retain the Council's trust, they proposed to share the additional costs between the laboratory and member states. From the 700MCHF overrun, the laboratory agreed to make savings of 300MCHF and share the remaining 400MCHF with member states. The laboratory savings even forced the closure of all machines for a year. As discussed in Section 5.2.2, CERN management also agreed to introduce a new project-tracking methodology - Earned Value Management. This served to provide additional

[71] The term MCHF is used in the CERN archives to refer to millions of Swiss Francs

tracking tools to both management and the CERN Council to prevent an additional crisis from developing.

A1.2.6 - 2008 magnet quench incident

After the 2001 budget crisis, the LHC project broadly ran without any other major issues. However, at the end of the project a new incident occurred that caused substantial damage to several magnets in the LHC. Towards the end of a CERN project, the new machine is handed over from project management to the laboratory departments for operation. Shortly after this milestone, on September 19th 2008, an incident caused damage to several magnets in the LHC tunnel. The subsequent investigation identified that a faulty magnetic connection caused an electrical arc, which damaged the cryogenic systems and caused a helium leak (CERN, 2008; Bajko *et al.*, 2009). During this helium leak, the helium transitioned from a superfluid state to a gas, causing a massive pressure increase and substantial damage to the LHC. Repair work took place over the traditional CERN winter shutdown and most of 2009 with first official operations delayed until November 2009. Even after the repair, CERN opted to reduce beam energy as there was still a significant risk of a repeat incident. Any major work to increase the maximum permissible energy had to wait until the long LHC shutdown from 2013 to 2015.

A1.2.7 - LHC first run (2009 to 2013)

In the first LHC run, the beam circulated initially at a reduced energy, although this increased over the course of the first run in response to greater confidence in machine capabilities. During this first run, the general-purpose detectors associated with the LHC considered in Chapter 5, ATLAS and CMS, found sufficient evidence to announce the discovery of the Higgs boson (Aad *et al.*, 2012; Riordan *et al.*, 2012).[72]

A1.2.8 - LHC long shutdown (2013 to 2015) and second run (2015 to present)

Following the conclusion of the first run wherein the Higgs was discovered, the LHC went into a long shutdown to complete upgrades to achieve much higher beam energies. While the first LHC run took place at energies of 3.5TeV per proton beam with collisions at 7TeV, these upgrades would enable collisions at 14TeV. There were no obvious issues

[72] The Higgs boson was originally theorised to be the quantum of the Higgs field (Higgs, 1964). In the standard model of particle physics the fundamental forces are composed of both a field and a corresponding particle (Perkins, 2000). The interaction of some particle types with this Higgs field explains why some particles have mass while other types do not interact with this field and are therefore massless (Riordan *et al.*, 2012). The Higgs boson was theorised to be quantum of the Higgs field (Higgs, 1964).

during the upgrade process, although during the recommissioning process ahead of the second run, there was a short circuit across two dipoles, which delayed collisions. A small metal fragment caused the short circuit but it did not become apparent until superfluid temperatures. The solution to resolve this issue was effectively to bring the helium to just above superfluid state and hit the metallic mass with a short but intense pulse of electricity to melt it. This successfully removed the short circuit issue and at the current time, there have been no major issues during the second run[73].

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[73] One minor issue did gain the attention of the press. A small rodent similar to a ferret managed to chew through a high voltage power supply in a surface-level electrical substation.

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Appendix 2 - Research documents

A2.1 - Interviewee information sheet

SPRU Science and Technology Policy Research

University of Sussex

Interviewee Information Sheet

Please read this carefully before completing the consent form. You may wish to save or print a copy for your personal records.

Project Title - Examining the Relationship between Leadership and Megascience Projects

This project has been approved by the Social Sciences, Arts and Humanities Cross-School Research Ethics Committee at the University of Sussex. [Reference number ER/DE51/1 Date of approval 19/11/2013]

Principal Researcher: Mr David Eggleton, Science & Technology Policy Research, Jubilee Building, University of Sussex, Brighton, BN1 9RH, United Kingdom

Supervisors: Dr Puay Tang and Professor Ben Martin

Email: d.eggleton@sussex.ac.uk

What is the purpose of this study?

The interviews are to add more detail to the information collected from the Fermilab History & Archives collections. We are interested in finding out your experiences of being a group leader or being part of a group. It would be helpful to hear about your educational background, including why you chose to enter particle physics, what characteristics you believe are conducive to being a good group leader and your attitudes towards groups. These interviews will help us to understand the characteristics of good group leaders and how and why these came about in the context of very large particle physics projects. This will be communicated to the wider communities of physics, science policy and management through the doctoral thesis. A copy of the final doctoral thesis can be sent you should you wish to see the final results although this is not mandatory.

Why have I been invited?

We were given permission by your colleagues to contact you as they said you might be willing to be interviewed as part of this research project. Your laboratory agreed to assist us because they felt this might be useful to apply the results of this research in future particle physics projects. This research has already been piloted within the Department of Physics at the University of Sussex. The department is also interested in knowing the outcome of this research. However **only** the researcher (David Eggleton) will have access to the raw data and only he will know who participates if you wish to include your name. All the data collected will be made anonymously. This means that no individual who participates will be recognisable.

Who is on the research team?

Dr Puay Tang and Professor Ben Martin are both researchers within the field of science policy and David Eggleton is carrying out this research as part of a PhD thesis. David Eggleton received his original training in Physics, and is educated to Masters degree level in the field.

Can I withdraw at any time?

Yes. Taking part in the interview process is entirely voluntary. If you choose to take part you still reserve the right to withdraw at any time and without giving a reason, either before or during the interview. This will not be known to anyone apart from yourself and the researcher. Your laboratory will not be aware of your participation or non-participation.

What happens when the study ends?

The results will be analysed and compiled into the doctoral thesis. This thesis will be available through the British Library. No individual interviewee will be identifiable from this thesis. Copies of the thesis will be available on request.

Confidentiality

All data will be collected and stored in accordance with the UK Data Protection Act 1988. This means that all of the information collected will be treated as confidential. It will not be added to your records at your laboratory. We will also ensure that information is stored securely and in an anonymous form. The raw notes, typed documents and all other data for this project will be stored securely at the University of Sussex and will not be available to anyone outside the research project.

Giving informed consent to take part

We would now like you to think about whether you would like to take part in an interview as part of this research. If so please reply to the email enquiry to which this document was attached (For clarity this email is d.eggleton@sussex.ac.uk).

Please note that before attending the interview you will be asked to read the statements on the consent form below. At the interview you will have an opportunity to ask further questions, and then be asked to sign this consent form to show that you agree to participate.

Thank you very much.

Mr David Eggleton

Doctoral Student

University of Sussex

A2.2 - Interviewee consent form

Consent for Participation in Interview Research

Project Title – Examining the Relationship between Leadership and Megascience Projects

I volunteer to participate in the above research project conducted by Mr David Eggleton from the University of Sussex. I understand that the project is designed to gather information about the nature of leadership within very large science projects. I have read and understood the Information Sheet, which I may keep for records. I will be one of approximately 30 people being interviewed for this research.

1. My participation in this project is voluntary. I understand that I will not be paid for my participation. I may withdraw and discontinue participation at any time without penalty. If I decline to participate or withdraw from the study, no one within my laboratory will be told.

2. If I feel uncomfortable in any way during the interview session, I have the right to decline to answer any question or to end the interview.

3. Participation involves being interviewed. The interview will last approximately 30-60 minutes. Notes will be written during the interview.

4. I understand that the researcher will not identify me by name in any reports using information obtained from this interview, and that my confidentiality as a participant in this study will remain secure. Subsequent uses of records and data will be subject to standard data use policies which protect the anonymity of individuals and institutions.

5. Faculty and administrators from my Laboratory will neither be present at the interview nor have access to raw notes or transcripts. This precaution will prevent my individual comments from having any negative repercussions.

6. I understand that this research study has been reviewed and approved by the Social Sciences, Arts and Humanities Cross-School Research Ethics Committee at the University of Sussex. For research problems or questions regarding subjects, the

Cross-School Research Ethics Committee may be contacted through Isla-Kate Morris at I.Morris@sussex.ac.uk.

7. I have read and understood the explanation provided to me. I have had all my questions answered to my satisfaction, and I voluntarily agree to participate in this study.

8. I have been given a copy of this consent form.

____________________________ ____________________________

My Signature Date

____________________________ ____________________________

My Printed Name Signature of the Investigator

For further information, please contact:
Mr David Eggleton,
Science & Technology Policy Research,
Jubilee Building,
University of Sussex,
Brighton,
BN1 9RH,
United Kingdom

Email: d.eggleton@sussex.ac.uk

A2.3 - Fermilab interview questionnaire

Interview Questionnaire

ALL INTERVIEW RESPONSES WILL BE CONFIDENTIAL AND ANONYMIZED

The questions below address management and leadership issues. Management and leadership differ in a number of crucial ways. Basically, management is a hands-on component of leadership - responsible for such functions as planning, organizing, controlling and ensuring assuming budgetary responsibility. Effective leadership is the ability to inspire followers to listen to and follow a vision and to achieve goals and to be innovative and creative.

GENERAL

1. How did you arrive at studying physics?
2. Why High Energy Physics?
3. How long did you work at Fermilab?
4. In what capacity? Project leader? Researcher?
5. Why did you join Fermilab?
6. [IF APPLICABLE: Where were you previously employed?]

VIEWS ON LEADERSHIP

1. What does it mean to you to be a leader?
2. What does being an effective or successful leader mean to you?
3. The literature on leadership suggests a number of leadership attributes. From the list below, which of them would you agree with? Disagree with?
4. Are there any other attributes that you think the literature has missed?
5. What do you think are the most important attributes of a good leader?
6. What do you think are the main obstacles to effective leadership?
7. In your experience, have you worked with a project leader who had difficulties with managing the project? What were the main difficulties experienced?
8. In your experience have you worked with a particularly good project leader? Why do you think he/she was a good project leader?
9. Do you think that people are born with leadership qualities? Or can be trained to be leaders? Or that leadership can be acquired, for instance, from learning by doing?

Research organization and management

1. What role does leadership play in a manager?
2. The literature tells us that the size of a research group can affect the management of a project in terms of, for instance, meeting objectives, encouraging initiative, establishing a spirit of cohesion and cooperation, coordination of tasks, keeping within the budget and the well-being of the research group. What do you think would be the ideal size for a research group for effective management? Why?
3. The literature also tells us that the size of a research group can affect the leadership style of the project leader. Would you agree with this view? If yes, why, if no why?
4. Conventional wisdom seems to tell us that scientists are intrinsically motivated by the science itself. Do you think that scientists in a project need motivation? If yes, why? How would you motivate them? If no, why not?
5. Did you have an opportunity to meet Leon Lederman? What kind of leader would you describe him to be?

A2.4 - CERN interview questionnaire

Interview Questionnaire

ALL INTERVIEW RESPONSES WILL BE CONFIDENTIAL AND ANONYMISED

The questions below address management and leadership issues. Management and leadership differ in a number of crucial ways. Basically, management is a hands-on component of leadership - responsible for such functions as planning, organising, controlling and ensuring assuming budgetary responsibility. Effective leadership is the ability to inspire followers to listen to and follow a vision and to achieve goals and to be innovative and creative.

GENERAL

7. How did you arrive at studying physics?
8. Why High Energy Physics?
9. How long did you work at CERN?
10. In what capacity? Project leader? Researcher?
11. Why did you join CERN?
12. [IF APPLICABLE: Where were you previously employed?]

VIEWS ON LEADERSHIP

10. What does it mean to you to be a leader?
11. What does being an effective or successful leader mean to you?
12. The literature on leadership suggests a number of leadership attributes. From the list below, which of them would you agree with? Disagree with?
13. Are there any other attributes that you think the literature has missed?
14. What do you think are the most important attributes of a good leader?
15. What do you think are the main obstacles to effective leadership?
16. In your experience, have you worked with a project leader who had difficulties with managing the project? What were the main difficulties experienced?
17. In your experience have you worked with a particularly good project leader? Why do you think he/she was a good project leader?
18. Do you think that people are born with leadership qualities? Or can be trained to be leaders? Or that leadership can be acquired, for instance, from learning by doing?

Research organization and management

6. What role does leadership play in a manager?
7. The literature tells us that the size of a research group can affect the management of a project in terms of, for instance, meeting objectives, encouraging initiative, establishing a spirit of cohesion and cooperation, coordination of tasks, keeping within the budget and the well-being of the research group. What do you think would be the ideal size for a research group for effective management? Why?
8. The literature also tells us that the size of a research group can affect the leadership style of the project leader. Would you agree with this view? If yes, why, if no why?
9. Conventional wisdom seems to tell us that scientists are intrinsically motivated by the science itself. Do you think that scientists in a project need motivation? If yes, why? How would you motivate them? If no, why not?
10. Did you have an opportunity to meet Lyn Evans/Chris Llewellyn Smith/Carlo Rubbia? What kind of leader would you describe them as?